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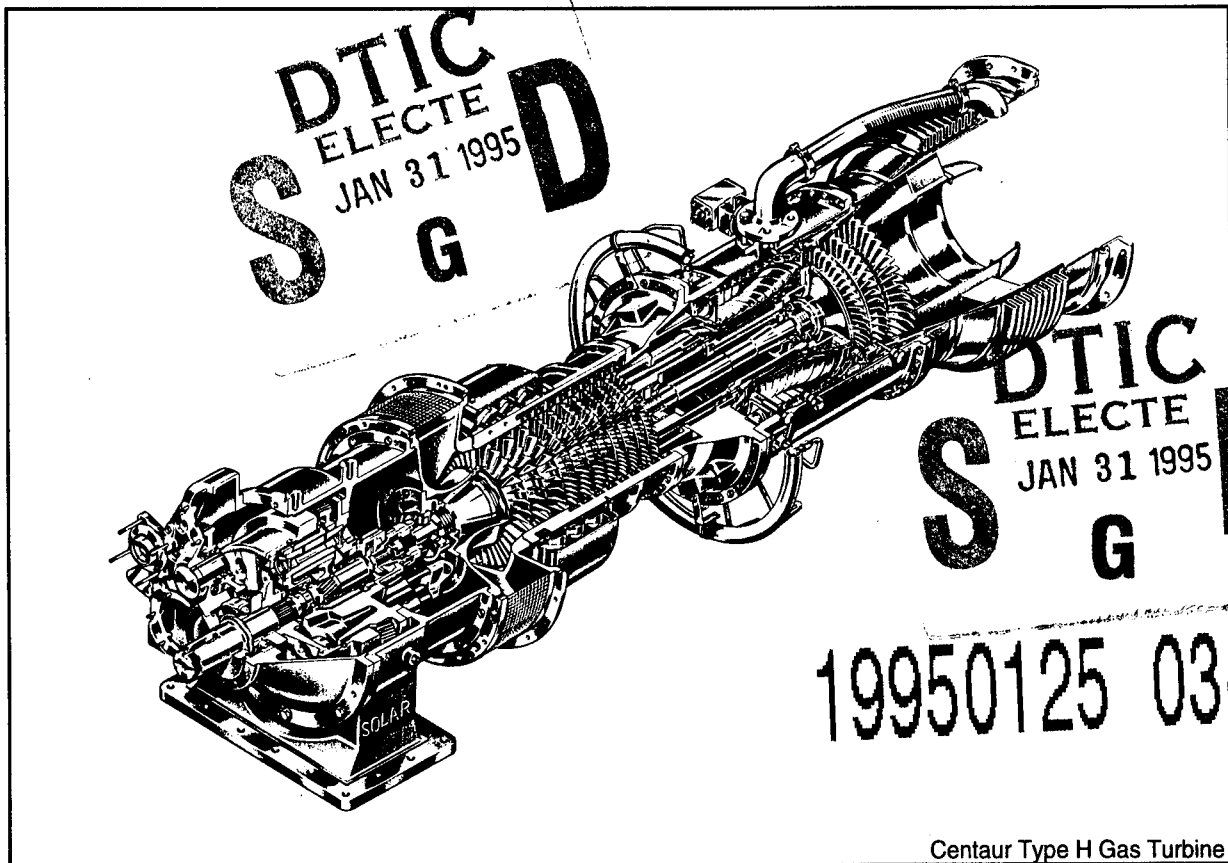
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Advanced Natural Gas Fuel Technologies for Military Installations

by

Martin J. Savoie, Patricia M. Freeman, Christopher F. Blazek, and Noel L. Potts



Centaur Type H Gas Turbine

Energy conservation efforts reduced Department of Defense (DOD) fossil fuel consumption considerably between FY85 and FY91, yet electricity consumption increased. Electricity consumption accounts for only one-third of DOD energy use, but over half of DOD energy costs. In addition, the production of electricity at coal or nuclear plants often creates environmental concerns, while the use of clean-burning natural gas does not; its use can help DOD bases comply with increasingly stringent environmental regulations.

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Recent developments in natural gas-fired technologies also demonstrate improved efficiency and productivity at lower costs. This report identifies state-of-the-art and emerging natural gas utilization technologies with potential application on DOD installations. This report describes various technologies that have potential residential, commercial, or industrial applications on DOD installations. Applications include heating, cooling, power generation, food preparation, and several industrial processes.

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FOREWORD

This work was performed for Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162784AT45, "Energy and Energy Conservation;" Work Unit EB-XX2, "Advanced Natural Gas Combustion Technologies," and for the Office of the Deputy Undersecretary of Defense, Environmental Security, Conservation and Installations (ODUSD/ES/C&I) under MIPR DSAM20076, dated September 1992; Work Unit RP3897WXI2, "Expansion of Natural Gas Utilization." The technical monitors were Harry Torabi, CEMP-ET, and Millard Carr, ODUSD/ES/C&I.

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ADVANCED NATURAL GAS FUEL TECHNOLOGIES FOR MILITARY INSTALLATIONS

1 INTRODUCTION

Background

Approximately two-thirds of the energy used by Department of Defense (DOD) facilities is provided by fossil fuels, including coal, residual oil, distillate oil, and natural gas, according to data from the Army Defense Energy Information System (DEIS). Fossil fuels are used primarily for space heating, domestic hot water, and industrial operations. Electrical energy accounts for the remaining portion of fixed facilities energy consumption.

Energy conservation efforts have reduced fossil fuel energy consumption considerably throughout DOD. For example, the Army has reduced its use of fossil fuels about 21 percent between Fiscal Year (FY) 85 and FY91 (DEIS). However, the overall energy reduction amounts to only 14 percent because of an 11 percent increase in electrical energy consumption. This growth caused the total reduction to be less and has actually led to an increase in energy costs. In the Army, electricity consumption represents only 29 percent of energy use, but amounts to 53 percent of total costs. These figures are similar for the entire DOD, where electricity consumption is roughly 33 percent of energy use, and 66 percent of total costs. The 1990 Federal energy policies set goals to achieve a 20 percent reduction by the year 2000 from the 1985 baseline (*FEMP Update 1991*).

These policies have also initiated procedures to integrate environmental benefits (e.g., cleaner air and reduced waste production) with energy conservation goals.

The U.S. Army Construction Engineering Research Laboratories (USACERL) is conducting research to help improve the efficiency and effectiveness of military installation energy use. The U.S. Army Center for Public Works' (USACPW) Energy System Modernization research program is developing procedures for extending the useful life of existing energy systems, improving fuel conversion efficiency, analyzing energy supply alternatives, and identifying and developing new technologies. Because natural gas fuel technologies have advanced more than any other category over the past decade, they are a major component of this research effort ("TERA Predicts Growth in Natural Gas Supply & Demand" 1991).

Many natural gas technologies now in use and under development not only can increase the combustion efficiency of gas operations, but may also replace or enhance oil- and coal-fired operations. In addition to improving the efficiency of oil and coal operations, gas can reduce pollution caused by these fuels. U.S. natural gas reserves are more abundant than oil reserves, and technologies that broaden the application of gas combustion will reduce the susceptibility of DOD operations to fluctuations in foreign oil supply.

Natural gas has the potential to supply a large portion of the energy required on military bases. Recent developments in gas-fueled technologies demonstrate better efficiency and productivity at lower energy costs. In addition, natural gas is a clean-burning fuel, which can help DOD bases to comply with increasingly stringent environmental regulations. Use of natural gas can reduce emissions in power generation, industrial processes, heating, and cooling. Cofiring or reburning with natural gas in coal operations or municipal solid waste (MSW) incineration can also reduce emissions. Therefore, state-of-the-art natural gas technologies need to be explored for possible use by DOD facilities.

Objective

The objective of this research effort was to identify state-of-the-art and emerging technologies for using natural gas as an energy source in DOD operations, placing an emphasis on technologies with potentially low pollutant emission levels and low operation and maintenance costs.

Approach

Trends in DOD natural gas consumption and U.S. natural gas production and costs were investigated. Advanced natural gas technologies were surveyed, and those with potential applications on DOD installations were identified. The technologies investigated address residential, commercial, and industrial applications, including space heating, space cooling, power production, pollution control, and several industrial processes. A brief description, including potential applications, was developed for each technology identified.

Scope

Although this is not a comprehensive list of all existing or developing gas-fueled technologies, the concepts covered in this report represent the full scope of natural gas technologies most applicable to U.S. military installations.

Mode of Technology Transfer

The findings of this study will help focus ongoing Energy System Modernization research. Research results will be used to update guidance documents, including *Heating, Energy Selection and Fuel Storage, Distribution, and Dispensing Systems* (Army Regulation [AR] 420-49); *Air-Conditioning, Evaporative Cooling, Dehumidification, and Mechanical Ventilation* (AR 420-53); *Mechanical Design: Heating, Ventilation, and Air-Conditioning* (Technical Manual [TM] 5-810-1); and *Air Pollution Control Systems for Boilers and Incinerators* (TM 5-815-1). Results will also be provided to the Navy and Air Force for updating their corresponding guidance documents. These will include: *Mechanical Engineering Power Plants* (Design Manual [DM]-3; *Pollution Control Systems* (DM-5.8); and *Steam Boilers and Equipment [500,000 - 18,000,000 Btu/h]* (Naval Facilities Guide Specifications [NFGS]-15631) for the Navy. The affected Air Force documents include: *Volume I: Heating Systems Policy* (Regulation [R] 91-7; *Volume I: General Operation and Maintenance of CHP and Distribution Systems* (Manual [M] 85-12); and *Volume II: Operation and Maintenance of Space Heating Equipment and Systems* (M 85-D).

2 DOD NATURAL GAS UTILIZATION

Natural Gas Supply Trends

According to a 1992 study by the Canadian Energy Research Institute (CERI), world gas production will almost double between 1990 and 2015 from 68.5 trillion cubic feet (tcf) to 132.5 tcf (*International Gas Technology Highlights* [IGTH] 24 August 1992). In order of production, the top three suppliers will be the Commonwealth of Independent States (CIS) and Eastern Europe, North America, and the Middle East. Correspondingly, CERI predicts world gas trade will grow 4.3 percent a year through 2015, reaching nearly 28 tcf annually. This increase in production and trade may result in a 1 percent annual increase in the average wellhead gas price rising from \$1.21/1000 cf in 1990 (U.S. dollars) to \$1.56 in 2015. Compensating for this increase, CERI predicts higher prices will enable construction of new facilities in emerging exporting nations, such as the CIS, and these new facilities will bring additional quantities of gas to the market. The acquisition price for these additional quantities and the current supply may rise from \$1.56 in 1991 to \$3.16 in 2010, as opposed to \$4.44 in the last baseline report, and over \$7.50 in the Gas Research Institute's (GRI) 1988 prediction (IGTH, 24 August 1992).

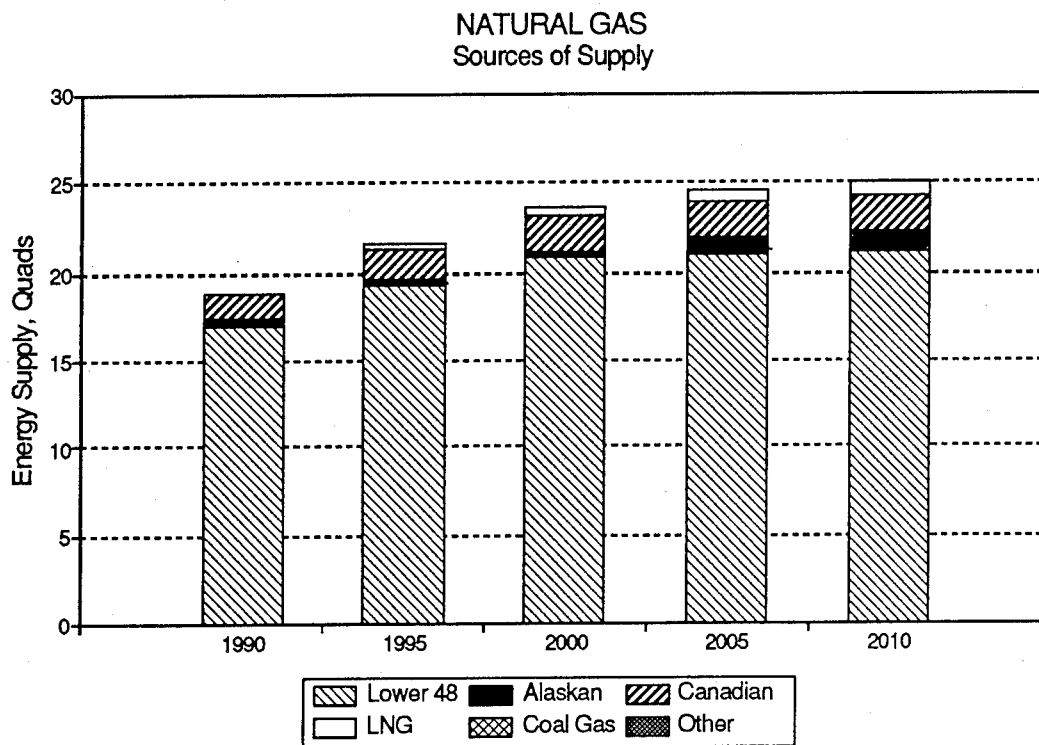
DOD installations will not be setting a new trend if they convert to natural gas technologies. The American Gas Association has reported that conversions of existing heating units to gas from other fuels rose 19.5 percent, to 261,700 in 1991. And despite a decline in housing completions last year, natural gas' share of the new housing market for both single- and multifamily homes rose from 55 to 56 percent (IGTH, 24 August 1992).

The sources of natural gas for U.S. consumption are plotted in Figure 1. Ninety percent of the U.S. natural gas supply is provided by domestic sources in the lower 48 states. The lower 48 supply is expected to increase from 16.5 tcf in 1990 to 20.8 trillion cubic feet (tcf) in 2010. Since U.S. gas consumption is projected to increase at a greater rate, the lower 48 will supply only 85 percent of the natural gas consumed in the U.S. in 2010. Sources imported from Canada are expected to increase to 1.8 tcf per year by the year 2000, and liquified natural gas (LNG) imports will grow to 0.4 tcf by 2000, and 0.6 tcf by 2010. Shipments from the Alaskan Pipeline are also expected to rise, reaching 0.8 tcf by 2010. Other sources of natural gas are expected to remain at the same levels.

The Total Energy Resource Analysis (TERA) predicts that natural gas prices for industrial users will remain competitive with electricity, fuel oil, and other fuel sources, as shown in Figure 2 (American Gas Association 1991). Natural gas costs will follow inflation until 1995 and then begin to rise at a higher rate, resulting in an average increase of 2.6 percent per year from 1990 to 2010. This price for natural gas is expected to be sufficient to encourage growth in well completions and reserve additions.

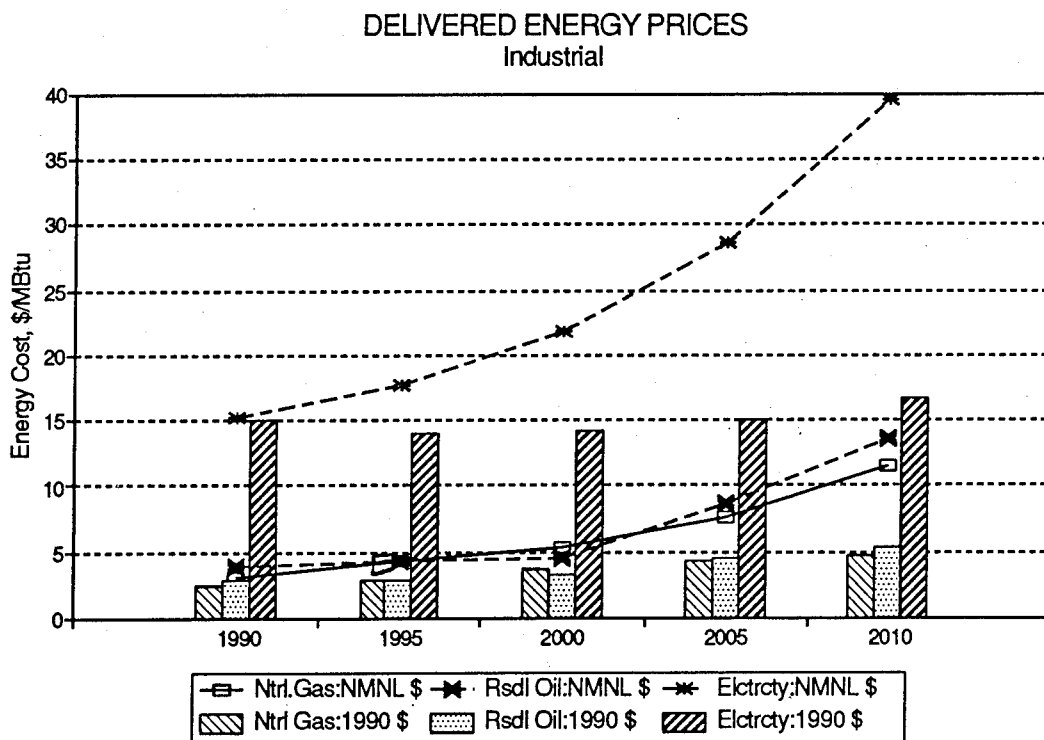
DOD Energy Strategy

In support of the National Energy Strategy (NES), DOD has issued guidance that directs military departments and defense agencies to reduce facility energy use and cost (Defense Management Review Decision 907). The 1990 energy goals require a 20 percent reduction in facility energy use within the next 10 years, based on 1985 energy consumption levels. In addition, the guidance specifically requires that the environmental benefits of energy conservation be included in the implementation goals for the 1990s. In particular, the environmental benefits of reducing air pollutants such as carbon monoxide (CO), carbon dioxide (CO₂), SO_x, and NO_x (sulfur and nitrogen oxides) emissions must be measured. The availability of environmental benefits will significantly affect which new fuel technologies are selected for use on military installations.



(Source: AGA, Summer 1991.)

Figure 1. Expected Growth in Natural Gas Sources.



(Source: AGA, Summer 1991.)

Figure 2. Expected Price Trend for Natural Gas.

DOD Energy Consumption

DOD energy use information is tracked through the Defense Energy Information System (DEIS), which was established to obtain energy consumption, inventory, and cost data from the military services. DEIS includes all purchased and nonpurchased energy consumption, except nuclear. DEIS information is typically used by installations and major commands to evaluate energy trends and determine progress toward energy goals.

Figure 3 shows the DODs overall annual consumption of the primary heating fuels and electricity for FY91 in the Continental United States (CONUS). It shows that the three major DOD organizations, Army, Air Force, and Navy (includes Marines) consume roughly the same amount of energy for fixed facilities. The proportions of fuel types are also similar with the exception of the Air Force which consumes more natural gas and less fuel oil than the other two services. The Army, Air Force, and Navy have each experienced reductions in energy consumption on a MBtu/ksf* basis from the 1985 baseline, 22 percent, 13 percent, and 10 percent, respectively. However, they have all experienced increases in electricity consumption (7 percent, 14 percent, and 39 percent, respectively), which have led to an overall increase in energy costs. Natural gas consumption has been fairly stable based on 1985 consumption.

Figure 4 shows the DOD energy consumption by source. Natural gas is the largest energy source, followed closely by electricity. Figures 5 and 6 show the total cost, and cost per MBtu respectively, for each energy source. Electricity accounts for over half of the energy costs. More importantly, Figure 6 shows that electricity is greater than 100 percent more expensive per MBtu. Figure 6 shows that natural gas is currently the cheapest energy source, after coal (coal has substantial costs associated with boiler plant operations).

Potential Cost Benefits of New Gas Applications

Application of new natural gas technologies, both conventional and advanced, could reduce DOD energy costs by improving the efficiency of existing natural gas systems, converting more expensive fuel technologies to natural gas, applying new technologies, and developing electrical generation capabilities. Figure 5 shows DOD energy costs for FY91. Despite the energy conservation efforts of the late 1980s and early 1990s, DOD energy costs are escalating. In FY91, the DOD spent over \$2 billion on heating fuels and electricity. Although electricity only accounts for about one-third of DOD's energy consumption, it makes up two-thirds of the energy bill. Figure 6 shows the cost of heating fuels compared to electricity in terms of dollars per million Btus. The cost per unit of energy for electricity is about four times higher than for heating fuels. On the basis of cost, it is obvious that electrical energy should not be the first choice to fulfill DOD energy requirements, especially for heating. With natural gas prices approximately \$3.50/MBtu compared to \$7.70/MBtu for distillate oil, gas is the preferable alternative to replace electrical energy. In addition to replacing electrical energy uses, the conversion of oil-fired boilers and heating systems to natural gas could save the Army \$70 million annually (DEIS).

It should be noted that economic analysis must be made on a life-cycle cost basis, including all capital equipment investments and operations and maintenance costs, not just on fuel costs.

*MBtu = Mega (1 million) British thermal units; ksf = thousand square feet.

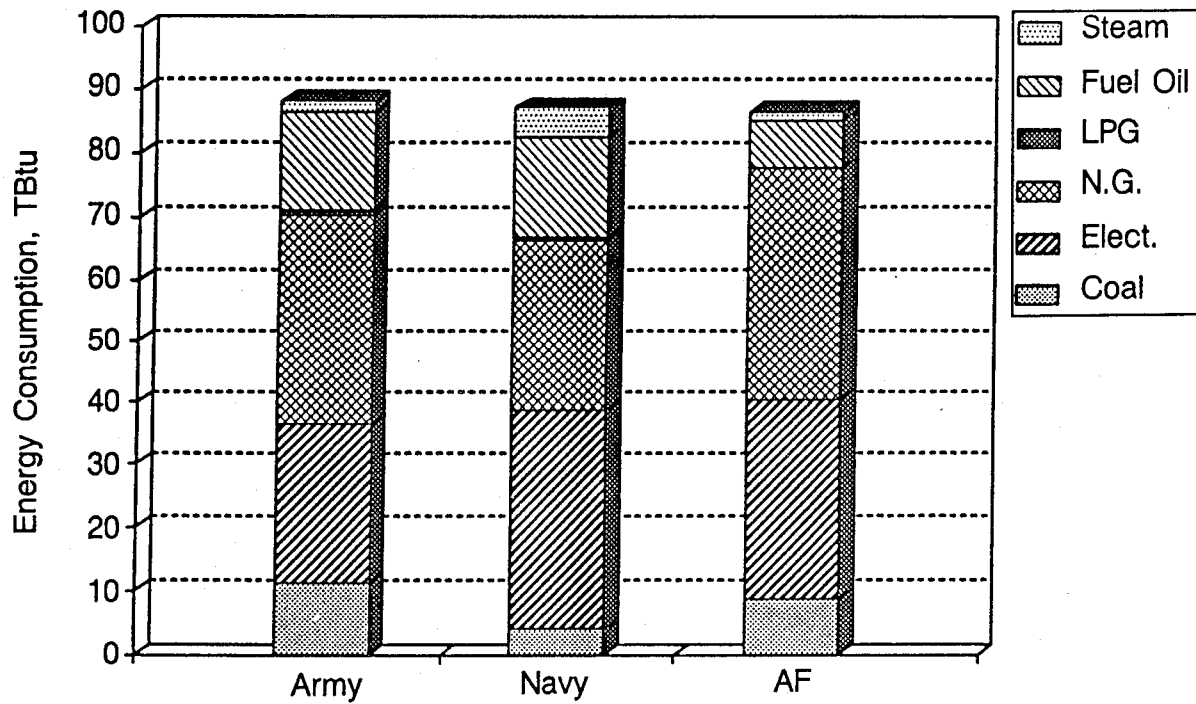


Figure 3. DOD Energy Consumption (TBtu) for FY91, CONUS.

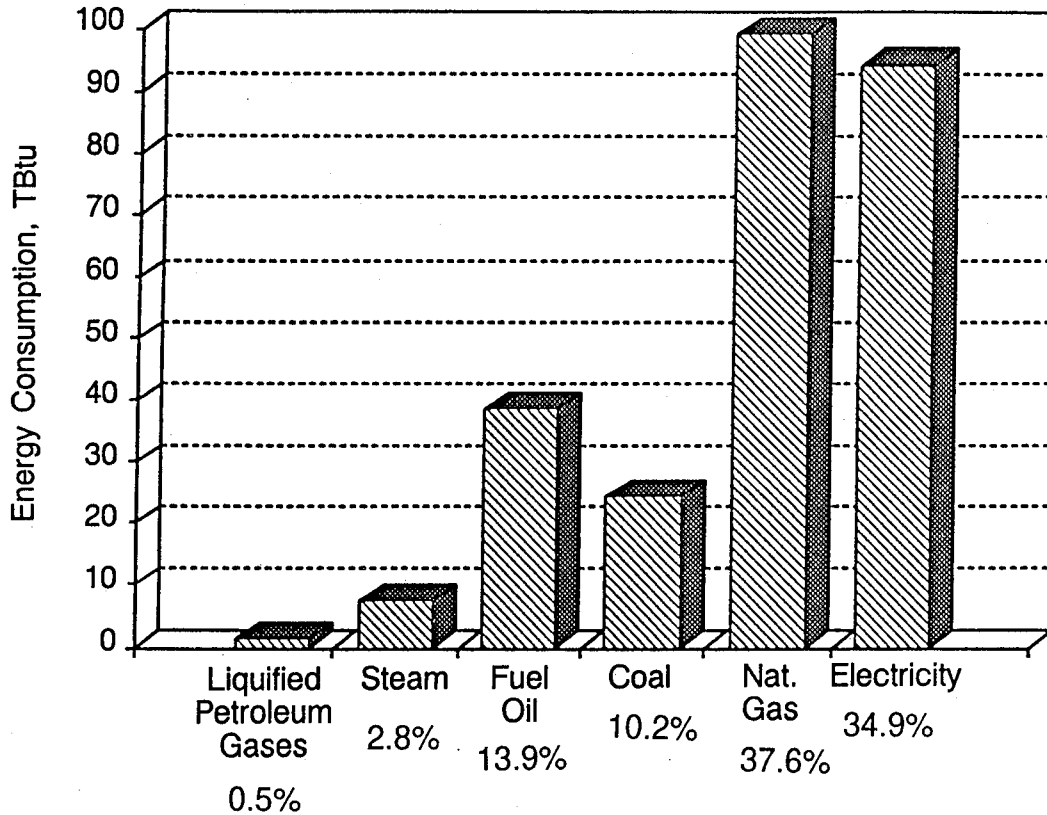


Figure 4. DOD Sources of Energy Consumption for FY91, CONUS.

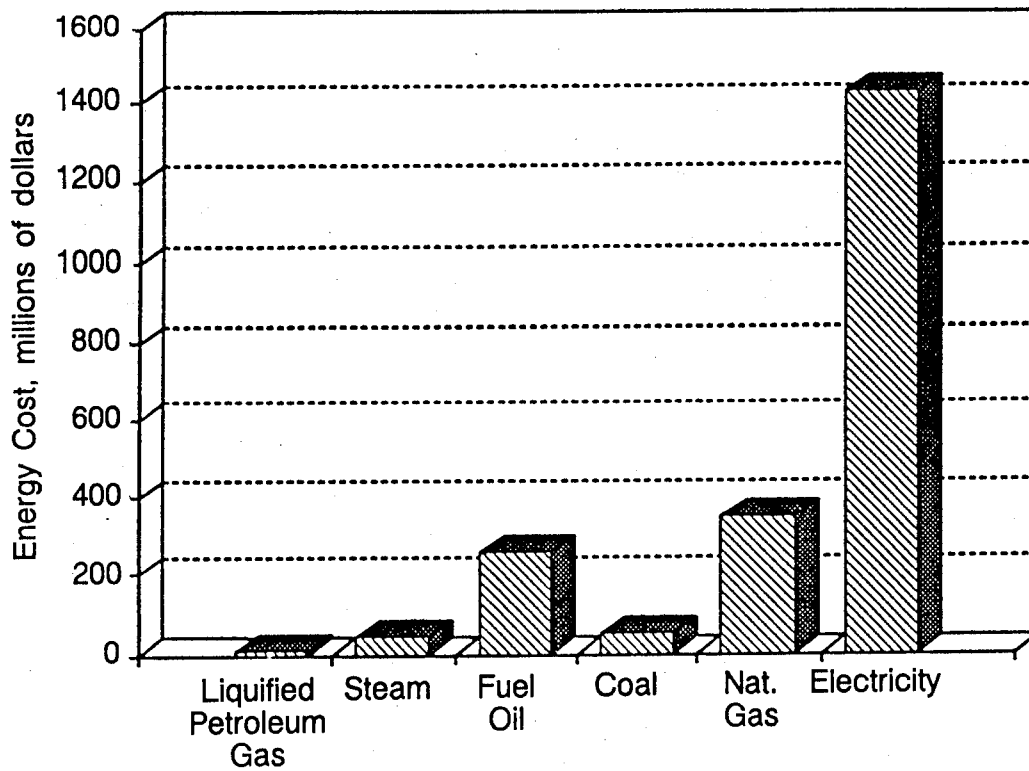


Figure 5. DOD Energy Costs in Millions of Dollars for FY91, CONUS.

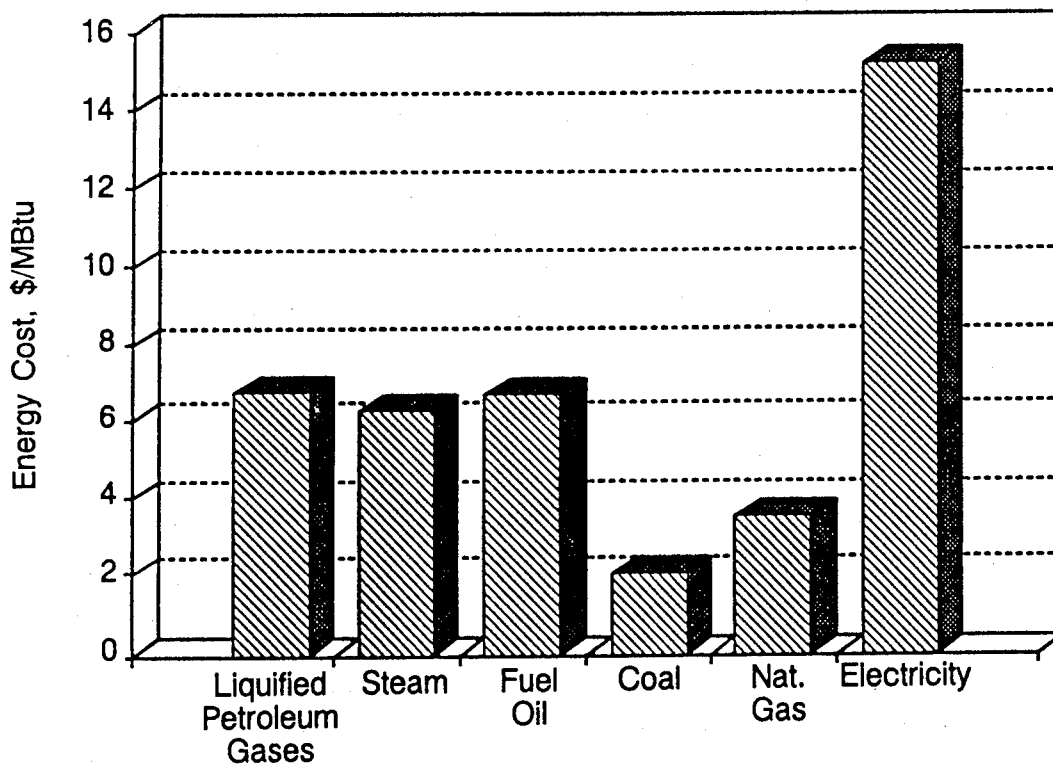


Figure 6. DOD Energy Cost in Dollars per MBtu for FY91, CONUS.

Potential Environmental Benefits of New Gas Applications

Natural gas combustion technologies typically produce less air emissions than oil or coal. Fuel switching could benefit many installations, particularly those in nonattainment areas for nitrogen oxides, ozone, and sulfur oxides. Figures 7 and 8 show an estimate of DOD air emissions from heating fuels and a projection of emissions if all fuel oil was converted to natural gas.

Air pollution emission estimates for heating fuels in Figures 7 and 8 were based on U.S. Environmental Protection Agency (USEPA) emission factors for external combustion sources, except for coal-fired boiler particulate emissions and all CO₂ emissions (USEPA 1988). The emission factor for coal-fired boilers was assumed to be 0.10 lb/MBtu, based on the DOD's extensive use of electrostatic precipitators and fabric filtration. An industrial source emission factor was assumed for natural gas and fuel oils, and a commercial emission factor was assumed for propane (USEPA 1988). CO₂ emissions were estimated by the gross calorific value method because USEPA emission factors were not available. To simplify calculations, all fuel oil was assumed to be No. 2, which provides a conservative emissions estimate.

Additional improvements in air emissions could be gained from electricity cogeneration technologies and natural gas chilling technologies. This is because the generation of an MBtu of electricity from fossil fuel is only about 32 percent efficient, compared to about 60 percent efficiency (including 15 percent distribution loss) for an MBtu of steam from a fossil fuel industrial boiler (Cook 1971). This is why it is typically not economical to use electricity for space heating and domestic hot water.

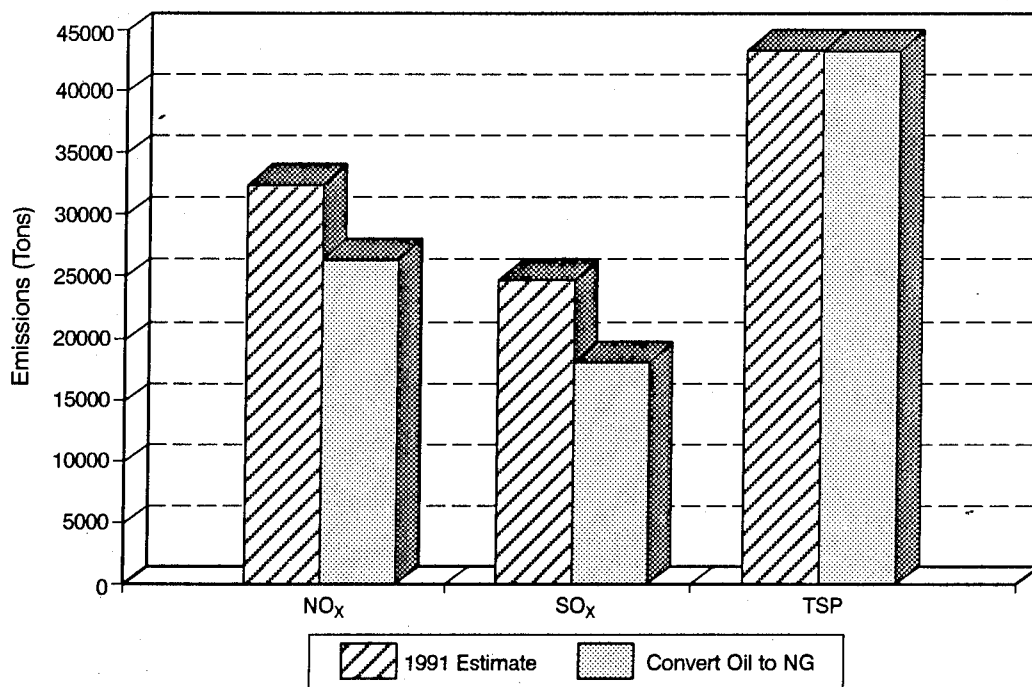


Figure 7. 1991 DOD NO_x and SO_x Emissions Using Natural Gas vs. Other Heating Fuels.

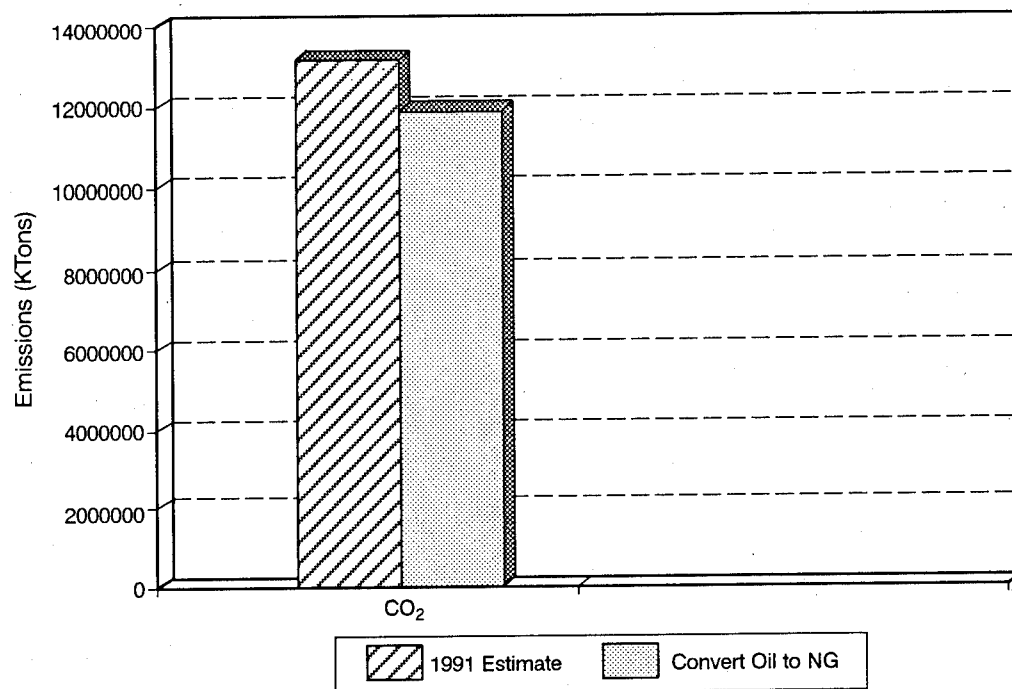


Figure 8. 1991 DOD CO₂ Emissions Using Natural Gas vs. Other Heating Fuels.

3 INDUSTRIAL POWER GENERATION

Increasing dependence on electrical energy has caused DOD energy costs to increase despite an overall decrease in energy consumption. The development of industrial-sized turbines (under 20 megawatts [MW]) has provided installations an opportunity to generate their own power and useful heat energy by-products (steam and hot water). The production of both electrical and useful heat energy is termed cogeneration.

Installing the capacity to produce all of an installation's power would be expensive because of the redundant equipment necessary to provide back-up power when one system is down for maintenance. The best alternative is to produce part of the electricity used by the installation and purchase the remainder. This allows the installation to reduce costly peak-demand costs and some of the usage costs. For most installations, the best techniques for industrial power generation are: steam turbines, gas turbines, reciprocating engines, and fuel cells. Each of these technologies can produce useful heat energy by-products. The technologies have applications at most installations, but their economics are dependent on utility power costs, fuel costs and availability, and the installation electricity demand profile. Steam and turbine technologies are normally associated with central energy plants, reciprocating engines may be in a central plant or located at facilities requiring emergency power (command centers, hospitals), and fuel-cell technologies have not had broad applications to date, but may utilized centrally or for individual buildings/facilities.

Combustion Technology

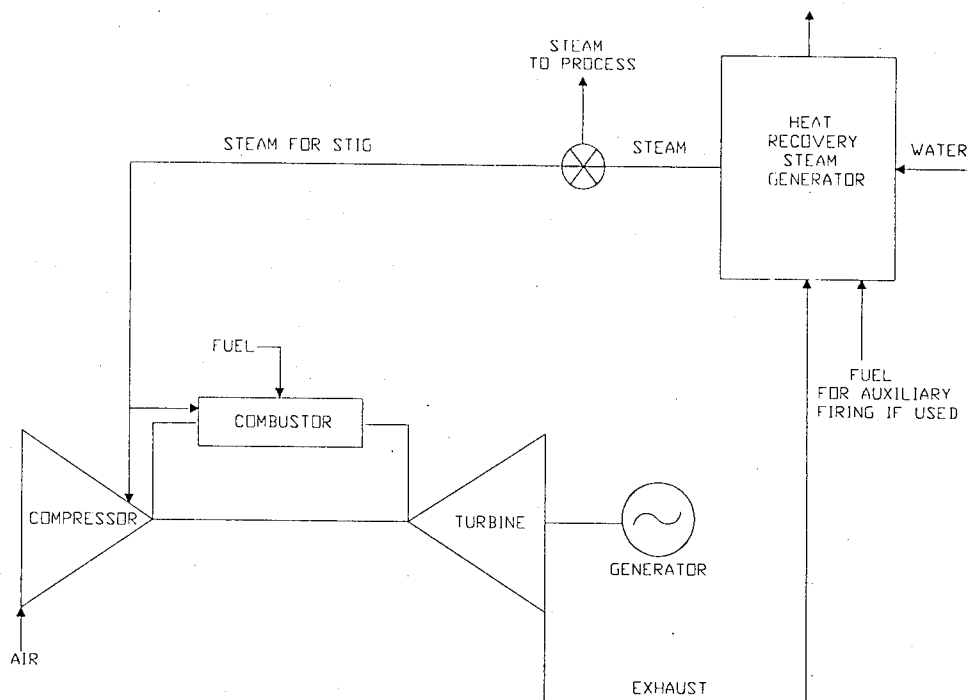
Steam-Injected Gas Turbine Cogeneration Systems

General Electric (GE) Company, with support from the GRI, is developing a steam-injected gas (STIG) turbine cogeneration system capable of providing variable power output and steam production.

A steam-injection system was added to the GE LM1600, a commercially available, easily maintained, and fuel-efficient gas turbine. The excess steam generated by the turbine exhaust heat can be used for process applications or recirculated into the turbine at 100 to 300 pounds per square inch (psi). Steam injection can reduce fuel consumption by up to 20 percent, or increase the electric output from 12 to 17.5 megawatts (MW), depending on the electric demand. Steam injection increases the efficiency from 36 percent to 40 percent (lower heating value [LHV]). A comparison of LM1600 performance in a simple cycle and a STIG configuration is shown in Figure 9.

A gas-fueled turbine with steam injection also reduces emissions. Nitrous oxide (NO_x) levels of 25 parts per million (ppm) at 15 percent O₂ are specified by GE. The steam-injected LM1600 is commercially available.

In addition to the GE LM1600, the Allison Gas Turbine Division of General Motors offers a STIG cogeneration system based on their model 501-KH gas turbine. The power output of the STIG 501-KH ranges from 3.2 to 4 MW, with 175 psi gage (psig) process steam produced at 20,000 to 35,000 pounds per hour (lb/h). Another company, European Gas Turbines, offers STIGs reported to increase turbine output by up to 20 percent, from 6 MW to 7.2 MW, with 11,000 lb/h steam.



(Source: *Gas Turbine World*, September-October 1990.)

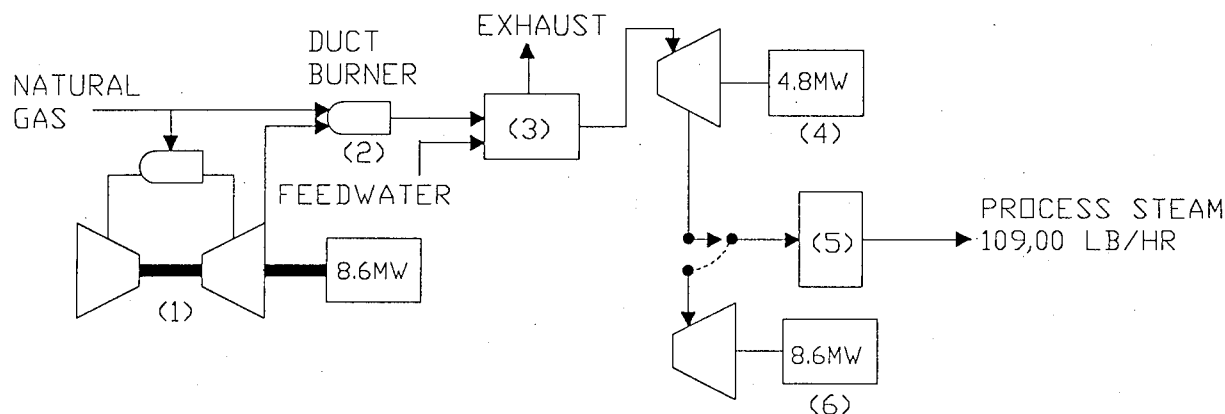
Figure 9. Simple Cycle vs STIG Performance of the GE LM1600 Gas Turbine.

Advanced Combined-Cycle Cogeneration System

Although very efficient for large plants, combined-cycle systems previously have not been cost-effective for plants under 20 MW because of the high capital cost and the relative inefficiency of small steam turbines. To solve this problem, Solar Turbines Inc., with support from GRI, has developed a 4.8 MW back-pressure steam turbine combined with an 8.6 MW gas turbine. A diagram of the system is shown in Figure 10.

The system includes a matched set of skid-mounted subsystems—a Solar Mars gas turbine/generator set with a Solar once-through heat-recovery steam generator (HRSG), and a newly designed two-stage back-pressure steam turbine/generator set. The advanced combined-cycle system can achieve an overall thermal efficiency of 75 percent. The high efficiency of the steam turbine is due to its high-temperature and high-pressure operation, advanced materials, and high rotational speed (30,000 revolutions per minute [rpm]). Variable thermal outputs (up to 109,000 lb of steam at 100 to 250 psi) and electrical outputs (8.6 to 13.4 MW) provide greater flexibility to accommodate fluctuating electric and thermal loads. An optional condensing steam turbine can be added to the system to convert the process steam to electricity for a total system output of 22 MW. The advanced boiler design also offers the capability of unattended operation and low emissions.

The modular construction and simplification of the steam generator and steam turbine results in a low capital cost, projected to be less than \$600 to \$700 per kilowatt (kW). To further reduce costs, the steam/generator set uses many components already produced for another project, the Centaur gas turbine/generator set. In addition, the system can produce 56 percent more electricity and three times more steam than conventional equipment in its size range. As a result, the return on investment (ROI) for the unit can reach up to 48 percent within 1 year, with a 2-year payback ("Combined-Cycle Cogen System



1. MARS GAS TURBINE-GENERATOR
2. DUCT BURNER
3. HEAT RECOVER STEAM BOILER
4. HIGH-PERFORMANCE BACK PRESSURE STM TURBINE
5. CONDENSING STM TURBINE

(Source: GRI Profile, March 1988.)

Figure 10. Solar Turbines Advanced Combined-Cycle Cogeneration System.

for Industry” 1991). Full-scale testing began in 1991, and the advanced combined-cycle cogeneration systems are expected to be commercially available from Solar Turbines by 1993.

Peakshaving Twin-Engine Cogeneration System

With support from GRI, Tecogen, Inc., has developed a peakshaving twin-engine cogeneration system. The system is designed to economically supply heat and electricity for buildings with a steady baseload energy demand, and to reduce the use of expensive utility peak electricity by doubling its speed and output during peak loads. The twin-engine system has a baseload capacity of 160 kW and a peak load capacity of 320 kW.

The system consists of two 454 cubic inch (cu in.) automotive-type, natural gas engines driven by a single 2-speed generator. The automotive engines are designed for high-speed operation, and are a fraction of the cost of industrial-grade engines. Engine life is extended by limiting the periods of peakshaving operation. The 2-speed generator is a conventional 4-pole, 3600 rpm induction unit with pole windings brought external to the generator for switching from 2-pole (1800 rpm) to 4-pole operation. A microprocessor control system provides both onsite and remote operation capabilities and enables automatic switching between peakshaving and baseload operation.

The lubricant oil system, jacket, and exhaust manifolds are cooled by a water-cooled heat recovery system. Two different coolant flow rates are supplied by two main circulating pumps to keep the engine temperature relatively constant at the two speeds.

Baseload power of 160 kW is supplied at 1800 rpm, with a peak load of 320 kW at 3600 rpm and a heat recovery rate of 1 to 2 million Btu per hour (MBtu/h). The system has projected electrical and

overall thermal efficiencies of 29.2 percent and 82.8 percent, respectively, and a 26 percent electrical efficiency in peakshaving operation. Due to lower capital costs and the peakshaving feature, Tecogen claims that this unit has a better payback than conventional cogeneration systems in most areas of the country. The system measures 10.5 ft x 7 ft, is 6 ft high, and weighs 10,000 lb.

The Tecogen peakshaving twin-engine cogeneration system has many possible DOD applications, such as hospitals and multifamily housing. The company has conducted field experiments with Baltimore Gas and Electric Co. at a Maryland hotel, and five prototype units were scheduled for field testing in early 1992.

Fuel Cell Technology

Fuel cell technology displays great potential as a clean and efficient energy source that can use a variety of fuels. A fuel cell is an electrochemical device that converts fuel directly into electricity and heat.

The benefits of fuel cells include a very high electrical generation efficiency in comparison to other sources of power generation, as shown in Figure 11. Since fuel cell efficiency is relatively independent of load, this technology is useful for onsite power generation and baseload power plants. In addition, the waste heat generated by fuel cells can be used for cogeneration applications. Fuel cells also produce low levels of emissions and noise, and the modular construction of fuel cell stacks allows the systems to range in size from less than a few kilowatts to multi-megawatt facilities.

Although fuel cells can use a variety of fuels, natural gas is well suited for the technology. Unlike gasified coal, natural gas contains few contaminants, requires minimal processing, and provides low energy costs.

Five types of fuel cells can be classified on the basis of the type of electrolyte used (Table 1). Three types most suitable for stationary power generation are the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). Each type has different operating requirements and performance characteristics that may be appropriate for different applications.

Phosphoric Acid Fuel Cell

Of the three types, the PAFC is closest to commercialization. The PAFC has a lower operating temperature and would be suitable for onsite residential and commercial applications to meet electrical demand and provide hot water and space heating. Larger PAFC plants are being developed for light industrial cogeneration.

A subsidiary of International Fuel Cells Corp. (IFC), ONSI (On-Site), Inc., is commercializing packaged PAFC combined heat and power generators up to 1 MW. Two 200 kW PAFC units, ONSI's first product, have recently been installed in the United States by Southern California Gas, and in Japan by Tokyo Gas and Osaka Gas. Sixty additional units are being manufactured for sites in the United States, Japan, and Europe. An electrical efficiency of 36 percent higher heating value (HHV) is projected with a net thermal efficiency of 80 percent HHV. The initial cost of the PAFC system is estimated to be \$1500/kW during 1995-97, and is expected to decrease to \$1000/kW by 1997-2000. Installation costs are estimated at \$250/kW with an operation and maintenance cost in the \$0.75/kWh range. The thermal output of the 200 kW PAFC unit is 800,000 Btu/h as hot water or low-pressure steam. Site interfaces of the 200 kW PAFC unit are illustrated in Figure 12.

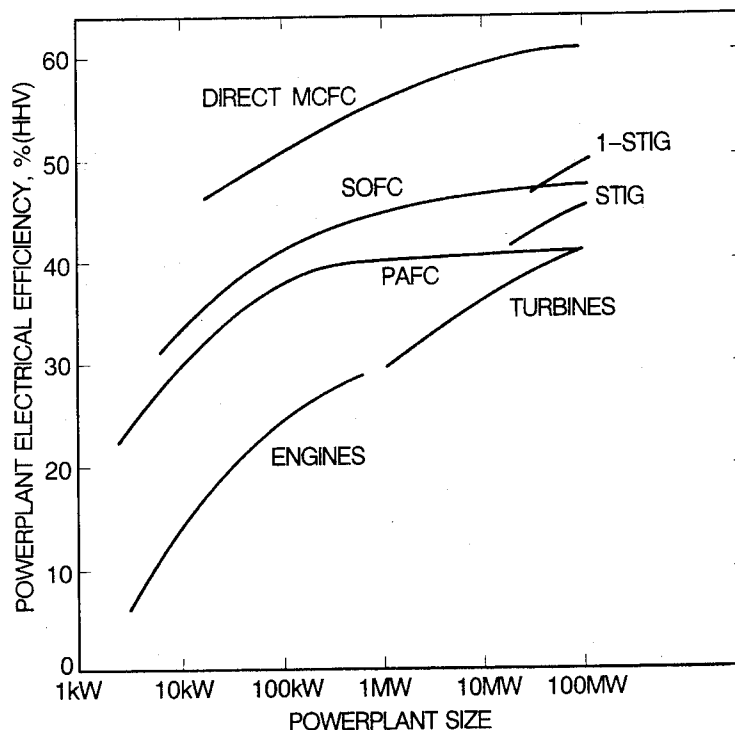


Figure 11. Comparative Efficiencies of Power Generating Technologies.

Fuji Electric and Osaka Gas are planning to commercialize packaged PAFCs for Japanese utilities. Installation of nine 50 kW units and seven 100 kW units is planned for 1993. These water-cooled systems are fueled by natural gas and designed to operate automatically. The electrical and overall efficiencies are projected to be 40 percent and 80 percent, respectively.

Molten Carbonate Fuel Cell

The MCFC is considered a second-generation fuel cell. Its development is not as advanced as the PAFC. The vendors involved in MCFC development and marketing include M-C Power (MCP), formed by IGT, IFC Corp., and Energy Research Corporation (ERC). Commercialization of MCFC systems up to 2 MW are planned by 1997. The cost of early production units is estimated at \$1500/kW while the cost of future units is projected to drop to about \$1000/kW. Both ERC and MCP are developing 250 kW MCFC stacks under a 3-year contract with the U.S. Department of Energy.

M-C Power is developing an internally manifolded, external reforming MCFC design that integrates the fuel reforming reaction with the fuel cell electrochemical reaction. A 250 kW prototype stack is planned for construction in 1993 and the production of commercial systems is projected to begin in 1995-96. An electrical efficiency of 48 to 50 percent is projected for units under 1 MW, and a higher efficiency of 55 to 60 percent HHV is estimated for stacks of more than 50 MW.

Five Japanese manufacturers (IHI, Mitsubishi, Fuji, Toshiba, and Hitachi) have also developed and tested MCFC units. The testing of a 1 MW MCFC unit is planned for 1995-1996.

Table 1

Comparison of Fuel Cell Types

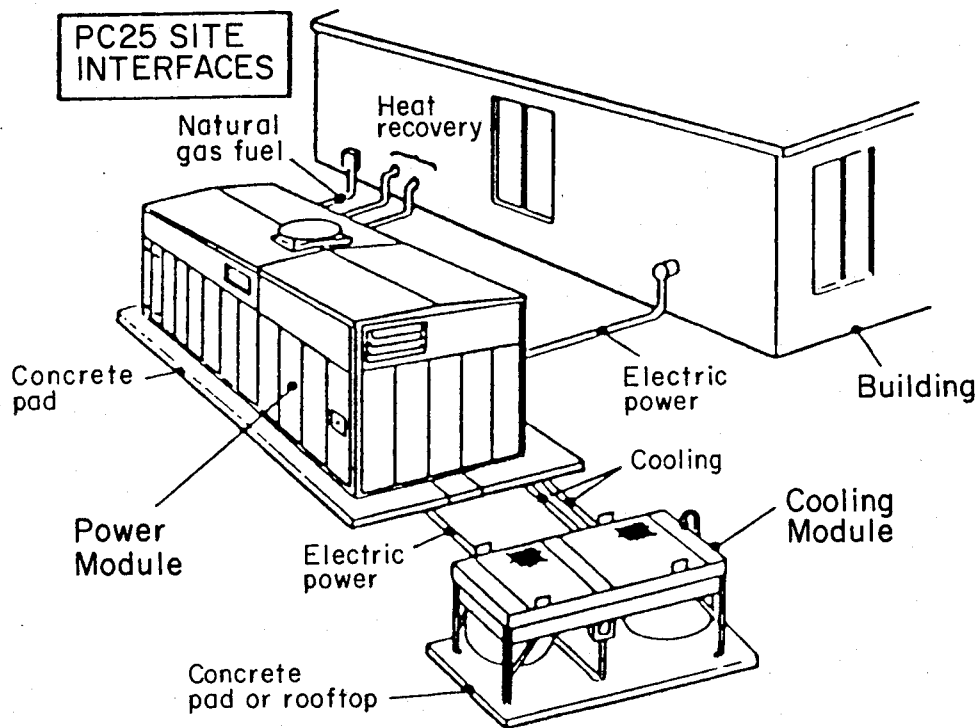
	PAFC	MCFC	SOFC	AFC	PEFC
Electrolyte	H ₃ PO ₄	Molten Salt	Ceramic	KOH/H ₂ O	Polymer
Operating Temperature	190 °C	650 °C	1000 °C	80/200 °C	80 °C
Fuels	H ₂ /Reformate	H ₂ /CO/Reformate	H ₂ /Reformate	H ₂	H ₂ /Reformate
Reforming	External	External/Internal?	External/Internal?		External
Oxidant	O ₂ /Air	CO ₂ , O ₂ , Air	O ₂ /Air	O ₂ /Air?	O ₂ /Air
Efficiency	40-50%	>60%?	>60%?	40-50%	40-50%
Scale	200 kW to 10 MW	>100 MW	>100 MW	0.1 to 20 kW	0.1 kW to 10 MW
Applications	Small Utility	Utility	Utility	Aerospace	Motive/Small

Source: Prater 1991.

Solid Oxide Fuel Cell

Commercialization of SOFC technology is not expected until 2000 and beyond. Westinghouse is a major developer of SOFC technology for utility applications. The company has successfully tested three 3 kW units in Japan and is currently building ten 20 kW units for Japanese utilities. As the first step toward commercialization, Westinghouse completed the construction of a Pre-Pilot Manufacturing Facility (PPMF) in 1989 with a projected capacity to manufacture 10,000 individual cells annually. With GRI support, Westinghouse is also investigating the concept of internal reforming natural gas within the tubular SOFC cell, a process known as "distributed reforming."

In Europe, Asea Brown Boverie (ABB) and Siemens are currently building 1 kW SOFC stacks to be completed by 1993. In Japan, Mitsubishi has built a 1 kW planar SOFC stack and a 2 kW stack using tubular cells. A 100 kW stack is planned for 1993-94.



(Source: Mulloney, D'Amore, and Miller 1991.)

Figure 12. Site Interfaces for the PC25 200 kW PAFC.

4 INDUSTRIAL BOILERS

DOD installations have several hundred industrial-sized boilers (10 to 200 MBtu/hr) operating on a variety of fuels, including natural gas, oil, coal, and municipal solid wastes. The average age of these boilers is about 35 years, many are past their expected useful life. The industrial-sized boilers are more prevalent in the northern portion of the United States because of heating requirements; however, many DOD weapons facilities use processes that also require large amounts of heat energy.

Cyclonic Combustion Boiler

Cyclonic combustion takes place in a cylindrical combustion chamber. Natural gas and air are injected tangentially at high speed producing a swirling combustion flow pattern as shown in Figure 13. This flow internally recirculates partially combusted hot gases, which intensifies and further stabilizes combustion. It also improves temperature and combustion uniformity, and reduces peak flame temperature to minimize NO_x formation.

Initial testing of a 40 horsepower (hp) cyclonic burner at IGT produced a stable flame and NO_x emissions of 20 ppm with combustion air staging. Even lower levels of NO_x emissions were achieved with excess-air firing. CO emissions were equal to or less than 50 ppm. With further development, the potential exists for additional reductions in both NO_x and CO emission levels. IGT is currently developing a 200 hp full-scale cyclonic burner designed for firetube boiler retrofits. This unit has emission goals of equal to or less than 15 ppm NO_x, 50 ppm CO, and 10 ppm total hydrocarbons (THC).

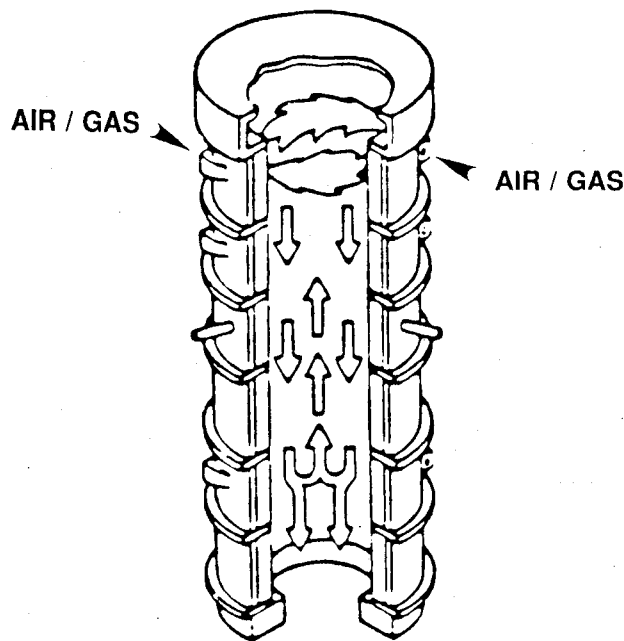
GRI/Donlee Advanced Industrial Boiler

With GRI support, Donlee Technologies, Inc., is developing an advanced gas-fired industrial boiler. The boiler design is a hybrid watertube/firetube boiler, and incorporates a cyclonic burner. The mixing and recirculation provided by the cyclonic gas flow increases convective heat transfer, producing stable combustion, low excess-air requirements, high turndown, and high efficiency. Enhanced heat transfer increases the boiler operating efficiency to 85 to 87 percent for all firing rates, and the unit can achieve almost 85 percent efficiency over a 10-to-1 turndown range. Improved efficiency allows the use of smaller units, resulting in lower capital costs. The recirculating flow pattern also reduces emission levels below conventional burner technologies, resulting in 25 ppm NO_x and 20 ppm CO. The design can be applied to boilers with capacities of 25 to 100 MBtu/h for use in a wide range of industrial processes.

Field tests of a 40 MBtu/h (1000 hp) boiler are being conducted. Preliminary results report an 85 percent fuel efficiency at high firing rates and an efficiency of 87 percent over a turndown ratio of 6 to 1, with excess combustion air of 0 to 15 percent. NO_x emissions were 40 to 50 ppm at a 6.5 to 1 combustion air-staging ratio without steam-injection. The addition of steam-injection to the cyclonic burner decreased NO_x levels to less than 30 ppm over the entire firing range. CO emissions were reported to be less than 50 ppm. In addition, the boiler demonstrated rapid startup (less than 30 minutes) and a quick response to changes in the steam load. Due to improved fuel efficiency, an energy savings of \$100,000 per year is projected for the field-test boiler. The advanced industrial boiler is expected to be commercially available from Donlee in 1992.

IGT/Donlee Turbofire™ Cyclonic Boiler

An advanced gas-fired firetube boiler developed by Donlee Technologies, Inc., is based on the patented cyclonic burner design by Donlee and IGT. The boiler is designed around a two-stage cyclonic



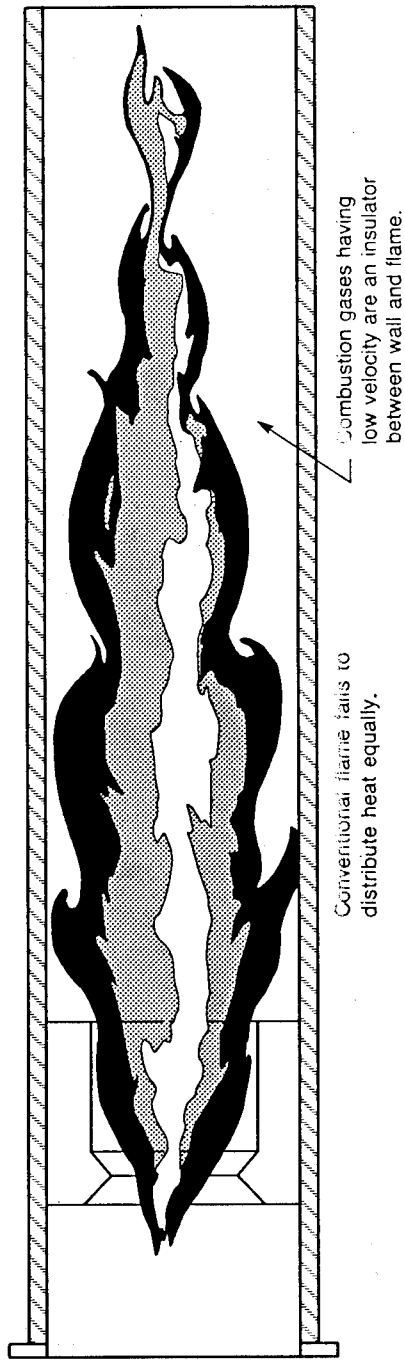
(Source: Xiong and Khinkis 1991.)

Figure 13. Flow Pattern in a Cyclonic Combustor.

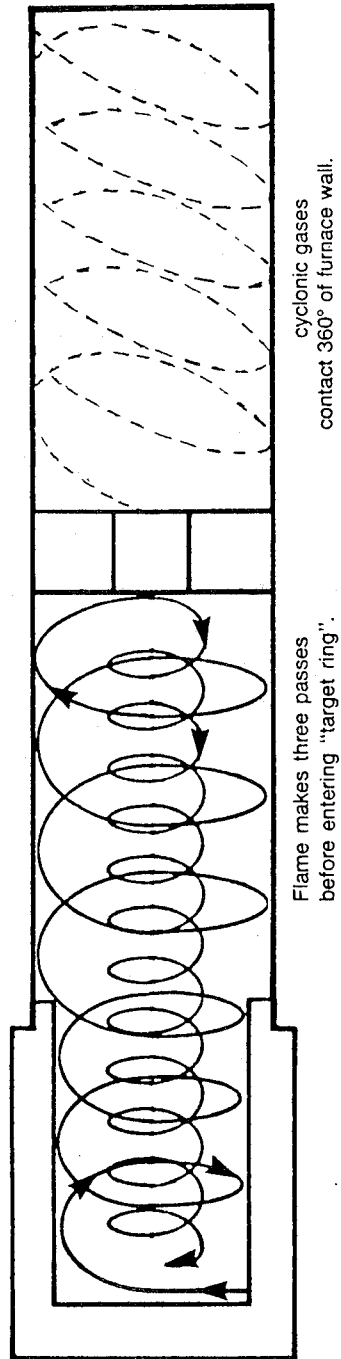
combustion system, and consists of a cylindrical water tube wall configuration with a heat exchange surface in the steam drum. The boiler has a three-pass design in which the flame makes three passes before entering the target zone, as shown in Figure 14. The swirling flame pattern produced by the cyclonic burner increases contact between the combustion gases and the boiler furnace wall, resulting in better heat transfer and higher efficiency. The cyclonic burner maintains a constant excess-air value, which allows the burner to maintain high efficiency even at reduced firing capacities. The water circulation system used in the TurboFire™ boiler provides quick heating, fast steaming, and high-quality dry steam. The large number of heating tubes allows a quick response to any load changes. In addition, a steam separator produces dry saturated steam with a moisture content of less than 0.5 percent.

The efficiency of the TurboFire™ boiler actually increases with reduced load reaching maximum efficiency in the normal operating range. The boiler exceeds 84 percent efficiency at 50 percent capacity. Sixty percent of the heat is released in the furnace, and the remaining 40 percent is released in the tubes. The improved heat transfer reduces the size of the unit necessary for a given capacity, so its capital cost is lower than for conventional units. The boiler also has low operating costs. The TurboFire™ boiler, targeted for the 750 to 1800 hp size range, is marketed by York-Shipley, a division of Donlee Technologies, Inc.

Conventional Flame Pattern



Flame Pattern



(Source: York-Shipley; reprinted with permission.)

Figure 14. Comparison of Conventional and TurboFire™ Flame Patterns.

5 INDUSTRIAL AIR-POLLUTION CONTROLS

A large number of DOD installations are located within areas designated by the Federal Environmental Protection Agency as nonattainment with air-quality standards. These areas are typically in major metropolitan areas. Several states, most notably California, have promulgated standards more stringent than the Federal standards to improve poor air quality. Many of the emerging natural gas fuel technologies have reduced air-emission characteristics making them more attractive in areas with air-pollution problems. In addition, using natural gas in conjunction with other fuels, such as coal and municipal solid waste, can reduce air pollutants.

The goal of the Clean Air Act (PL 101-549) is to reduce the amount of these pollutant emissions, specifically NO_x, SO₂, and CO₂, from fossil fuel boilers. While industrial boilers are not required to meet these restrictions, emission reduction credits and allowances authorized by the law can be sold, traded, or used, providing economic incentive for voluntary compliance by unregulated operators. In most cases, meeting the standards involves the use of retrofit emission control systems.

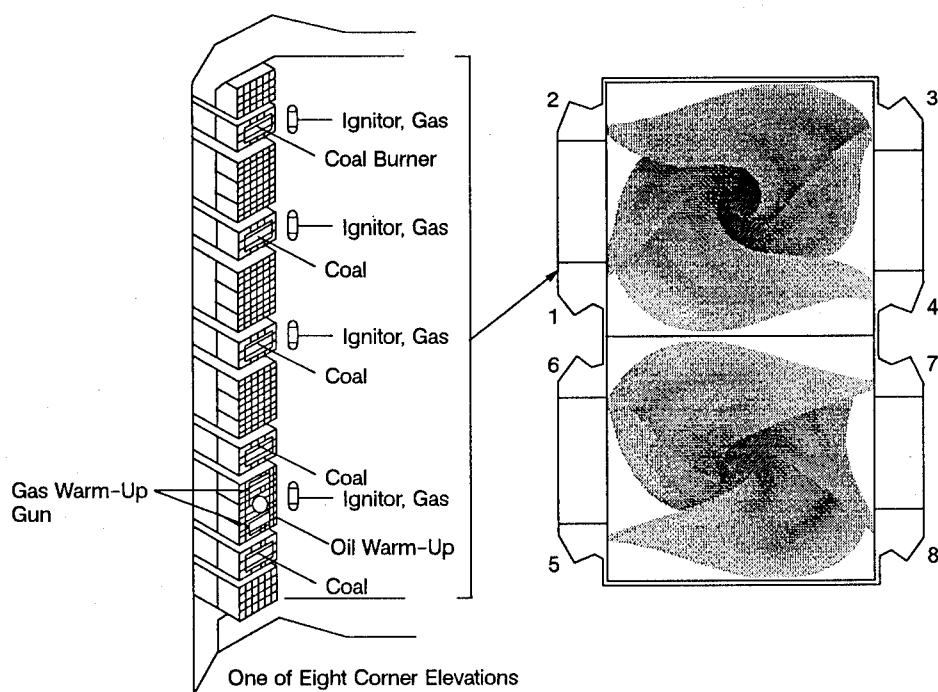
Coal combustion produces almost three-fourths of all CO₂ emissions and nearly one-third of all NO_x emissions in the United States. In contrast, natural gas is a clean-burning fuel that produces minimal sulfur oxides, reactive hydrocarbons, and particulates. Per unit of energy, natural gas combustion results in lower levels of NO_x than oil or coal and almost half the amount of CO₂ produced by coal-fired boilers. Natural gas cofiring and reburning technology added to coal boilers can provide efficient, cost-effective options for controlling emissions and can also improve boiler performance and extend equipment life. The technologies described in this chapter use natural gas to reduce emissions: cofiring, gas reburning combined with low NO_x burners and sorbent injection, and natural gas injection for MSW incineration.

Natural Gas Cofiring

In basic cofiring, natural gas is injected into the combustion zone with coal, displacing some of the coal energy. Since natural gas does not contain sulfur or nitrogen, and contains only a fraction of the carbon in coal, this results in an overall reduction of SO₂, NO_x, and particulates. Gas cofiring involves low capital costs, so it is well suited for boilers requiring only a slight reduction in SO₂ or NO_x. In addition, by stabilizing the coal burner flame, gas cofiring can potentially improve boiler efficiency, startup time, turndown, availability, operation, and maintenance.

Field tests of basic cofiring were conducted in 1986 and 1987 by Energy Systems Associates, GRI, Duquesne Light, Consolidated Natural Gas Co., and Peoples Natural Gas Co. on a 570 MW, tangentially fired boiler. The igniter and warmup system of the coal-fired boiler were converted to dual-fuel (natural gas and oil) operation. Figure 15 illustrates the placement of the natural gas igniters and warmup guns, and the resulting flame pattern. Initial tests demonstrate a reduction of emissions and a possible improvement in boiler performance.

Field tests of this technology were followed by experiments in 1989 at the Public Service Company of Oklahoma's Northeastern Station (NES) near Tulsa. In short-term results, cofiring of 10 percent natural gas and 90 percent coal at NES reduced SO₂ emissions by 15 percent and emission opacity by 30 percent. Additional tests were conducted on two wall-fired boilers by the Aluminum Company of America (Alcoa) and Southern Indiana Gas & Electric Co. (SIGECO) in Warrick County, IN.



(Source: GRI, September 1987).

Figure 15. Schematic of Cofiring Technology and Resulting Flame Pattern in Cheswick Twin-Furnace Boiler.

Natural Gas Reburning

In gas reburn systems, the combustion process takes place in three stages, as shown in Figure 16. In the main combustion zone, a reduced amount of coal is fired in the boiler for most (80 to 85 percent) of its heat input. Natural gas is then injected above the coal burners, adding heat to convert much of the NO_x formed by combustion to molecular nitrogen. Air is added above the reburn zone to complete combustion at lower temperatures, minimizing additional NO_x formation.

Gas reburning can reduce NO_x levels 50 to 60 percent, and SO₂ reduction is proportional to the amount of natural gas used. Gas reburning can be applied to all types of boilers currently in use. However, the technology is best suited for boilers that require (1) high NO_x reductions and small SO₂ reductions and (2) are not easily compatible with low NO_x coal-burning modifications or coal switching.

With support from GRI and the Electric Power Research Institute (EPRI), Babcock & Wilcox is conducting a pilot-scale test on a 5 MBtu/h cyclone furnace with 22 percent natural gas injection. A 60 to 95 percent decrease in NO_x levels has been achieved and the CO₂ emissions dropped below baseline levels. In preliminary tests at a 108 MW cyclone-fired boiler at Ohio Edison's Niles Power Station in December 1990, 20 percent gas input reportedly reduced NO_x emissions by 50 percent.

Gas Reburning/Sorbent Injection

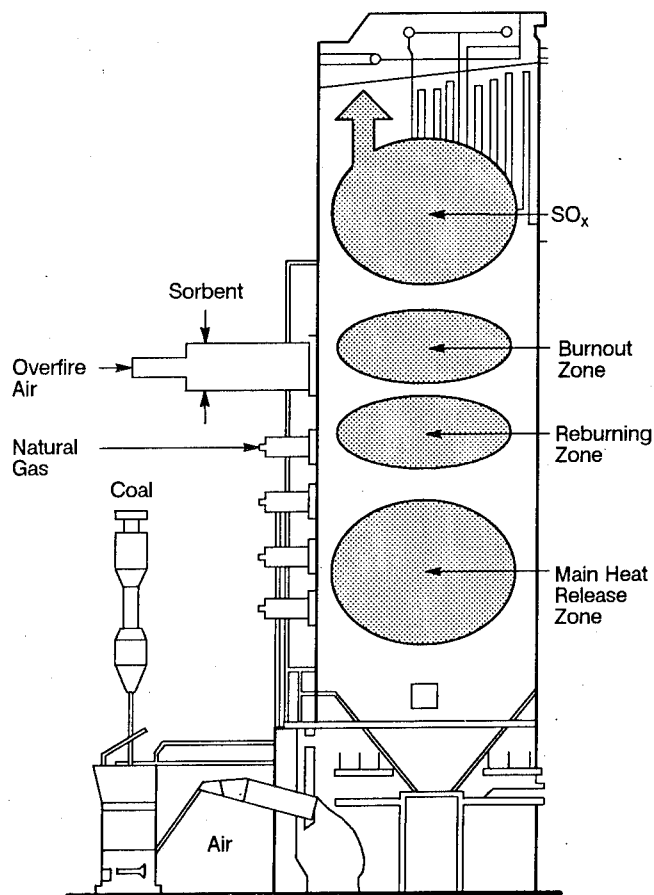
Gas reburning combined with sorbent injection (GRSI) blends effective NO_x removal with SO₂ emission control. As a post-combustion technology, sulfur-capturing sorbent is injected into the boiler or the flue gas duct. The sorbent reacts with SO₂ and forms solid compounds that are removed by an

electrostatic precipitator (ESP) or baghouse. The GRSI system has great potential for reducing emissions from older or tightly spaced plants that cannot house large, complex pollution control systems. The GRSI system can also be installed with a plant's existing burners or combustors, which significantly reduces capital costs.

Illinois Power Co.'s Hennepin Plant is an operating, tangentially fired 71 MW coal boiler. The Energy and Environmental Research Corp. (EERC) conducted a series of 2-hour, steady-state gas reburning tests in December 1990 and January 1991 on the Hennepin plant and reported a 68 percent reduction in NO_x emissions. Natural gas contributed 18 percent of the total heat input during the tests. The project is continuing and the testing of gas reburning combined with sorbent injection will begin in April 1992. Long-term GRSI testing will follow. In addition, EERC will begin testing GRSI technology on a 30 MW cyclone boiler at Lakeside Station in Springfield, IL in the fall of 1992. This will provide important information on the performance of GRSI systems installed on coal-fired cyclone boilers.

Gas Reburning Low-NO_x Burners

Combining gas reburning with low-NO_x coal-burner technology promises to provide low emissions at a lower cost compared to conventional emission-control technology. To examine the performance of this combination, gas reburning is being added to a wall-fired utility boiler in research jointly funded by Government and private industry.



(Source: AGA, Spring 1991.)

Figure 16. Natural Gas Reburning System for a Wall-Fired Burner.

Individually, gas reburning in a coal-fired utility boiler has been reported to reduce NOx emissions by 50 to 60 percent, and low-NOx coal burners have produced a 15 to 50 percent decrease in emissions. The goal of this research, funded by GRI, the U.S. Department of Energy (DOE), Colorado Interstate Gas Co., and EPRI is to achieve more than a 70 percent reduction in NOx emissions. The equipment was designed by EERC. Testing of the wall-fired unit at Cherokee Station Unit 3, owned and operated by Public Service Company of Colorado, was scheduled to begin in spring 1992 with a low-sulfur western coal.

Natural Gas Injection for MSW Incineration

Increasing environmental restrictions on the disposal of MSW in landfills have prompted the development of MSW combustion systems that would allow waste-to-energy plants to meet EPA emission standards. Riley Stoker Corp., Takuma Co. Ltd., GRI, IGT, and Olmsted County, MN, have jointly developed a MSW combustion system that uses natural gas injection to control emission levels. The Methane de-NOx™ process prevents the formation of nitrogen-containing chemicals such as ammonia, which rapidly burns to form nitrogen oxides. These reactions are prevented by controlling the amount of air in the combustor and adding controlled amounts of natural gas and air into the combustion space above the MSW incinerator's main flame. This technique also reduces CO and hydrocarbon emissions. Furthermore, the heating value of the natural gas is used for energy production. The Methane de-NOx™ system is more efficient and cost-effective than other emission controls that allow NOx formation, then remove it later at an additional cost.

A 30-day field test was conducted at the Olmsted County waste-to-energy facility on one of two 100 tons-per-day (tpd) Riley/Takuma mass-burn combustors. With gas injection of 14 percent total heat input and 7 percent oxygen, the Methane de-NOx™ system achieved NOx levels below 75 ppm, well under the USEPA standard of 180 ppm, and CO levels were less than 40 ppm. This resulted in a 60 percent reduction of NOx emissions and a 50 percent reduction in CO, compared to baseline levels. MSW feed rates were maintained at the baseline level. In addition, natural gas injection provided a reduction in excess air while flue gas recirculation levels of 6 to 8 percent were sufficient to inject and effectively mix the natural gas. IGT has received a patent for the Methane de-NOx™ process. Large-scale field demonstrations are planned, and the system is projected to be commercially available in 1993.

6 INDUSTRIAL PROCESS APPLICATIONS

DOD weapons facilities perform a wide variety of industrial operations in the manufacture of munitions, weapon systems, tactical vehicles, aircraft, and naval vessels. Recent military force downsizing and facility consolidation provides an opportunity to upgrade remaining facilities with more efficient and less polluting equipment.

This chapter describes emerging industrial process applications for the general areas of industrial burners, furnaces, glass manufacturing, drying, and compressors. Industrial burners are used in processes such as the hardening of gun tubes and curing of coatings. Industrial furnaces have many applications in raw material processing and manufacturing, including heat treatment, hardening of metal components, and cement manufacturing. Industrial dryers also have many process applications. A slurry drying process that may have applications in munitions manufacture, a drying process for regenerating desiccant cartridges, and material drying process with application in manufacturing and food processing will be described. Many DOD installations use compressed air to operate tools and machinery. Gas-driven compressors can reduce peak electric demands and provide a heat source for drying compressed air.

Industrial Burners

Gas-Fired Radiant Burners

In radiant burners, combustion takes place near or on the surface of a high-temperature noncombustible material. Heat is transferred to the load by convection and radiant heat transfer. Gas-fired radiant burners provide high energy density, flexible control of heat transfer, and low emission levels. The two types of radiant burners are indirect-fired and direct-fired. Indirect-fired burners separate the combustion products from the load, whereas direct-fired burners deliver hot exhaust gases directly into the furnace. Direct systems have a higher efficiency, but since the products of combustion are mixed with the delivery air stream, emission levels are a potential problem.

Indirect-Fired Radiant Tube Burners

Indirect radiant burners were developed for applications that require high-temperature treatment of materials with no contamination by the products of combustion. Natural gas is burned within the tube, and the walls of the tube are heated by the flame and the hot exhaust gases. The load, in turn, is heated by radiant heat transfer from the outer surface of the tube. The thermal efficiencies of the radiant burner can be as low as 33 percent, but with the addition of heat exchangers and heat-recovery technology, system efficiency can reach 40 to 50 percent.

Operating temperature is determined by the material of the tube. High-temperature metals can withstand up to 2000 °F and are commonly used for process operations below 1900 °F. Although metallic radiant tubes are used for indirect-fired heat-treating of metal, electric heating elements are typically used for processes in which the temperature or heating rates exceed the capacity of the metal tubes. A gas-fired burner that handles higher temperatures and higher heating rates would offer a lower-cost alternative to electric furnaces. With the development of high-temperature ceramics such as the Coors SCRB 210 silicon carbide, radiant tube burners can withstand maximum operating temperatures up to 2500 °F.

Radiant Tube Burners

With GRI support, both Pyronics, Inc., and Eclipse, Inc., have developed single-ended recuperative (SER) radiant tube burners. As shown in Figure 17, several configurations of radiant tube burner systems currently exist. SER tubes are made of reaction-bonded silicon carbide ceramics and consist of an outer radiant tube and an inner combustion tube nested concentrically, as illustrated in Figure 18. A mixture of air and fuel flows through the burner nozzle and is ignited by an electric spark wand within the tube. The heat from the exhaust gases is transferred to the outer radiant tube by convection and radiation. The heat is transferred to the furnace by radiation from the surface of the outer wall. The heat from the exhaust gases is recovered by a high-efficiency recuperator and used to preheat the combustion air.

Compared to metallic tubes, which are limited to 1900 °F, the ceramic material of SER tubes can withstand temperatures up to 2500 °F, thus expanding the applications and temperature range of gas-fired furnaces. The ceramic radiant tube burner increases thermal efficiencies by 50 percent over electric-resistance heaters, reducing energy costs by 50 percent and improving production rates. The use of SER technology also reduces furnace size and capital costs.

Laboratory tests demonstrated a maximum operating temperature of 2500 °F and a temperature variation on the radiant tube of only 30 °F for a furnace chamber temperature of 2200 °F with 10 percent excess air. The average thermal efficiency was 58 percent for a furnace temperature of 1800 to 2200 °F, 150 Btu/h/sq in. heat flux, and 15 percent excess air. CO emissions were reported less than 60 ppm and NO_x levels of less than 600 ppm. Field tests were conducted on retrofit units and verified the efficiency and performance of the ceramic SER gas-fired radiant tube burner. These gas-fired SER radiant tube burners are now commercially available from Eclipse, Inc., and Pyronics, Inc.

Direct-Fired Radiant Burners

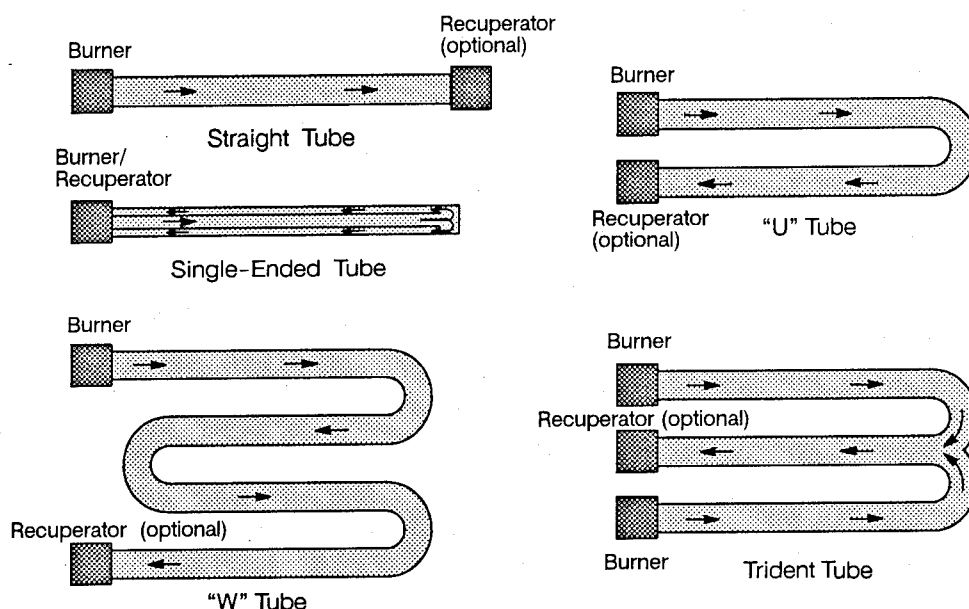
For low-temperature industrial drying and heating applications, gas-fired systems are generally preferred over electrical heating because gas costs less. Direct-fired gas burners have a higher efficiency than indirect-fired burners which transfer heat through a heat exchanger. A disadvantage of direct-fired burners is that the products of combustion come into direct contact with the load, and can contaminate sensitive products such as food.

In a direct-fired radiant burner, a mixture of natural gas and air is ignited at or just below the surface of a refractory material. The refractory surface can be made of ceramic fiber, metal fiber, porous ceramic foam, or perforated ceramic tile. The surface temperatures can range from 1600 to 2250 °F, with heat rates of 40,000 to 120,000 Btu/h/cf.* The benefits of surface combustors include uniform heat release, which is critical in sensitive moisture removal operations such as the drying of paper, textiles, and paint. Another benefit is the low levels of NO_x produced, ranging from 15 to 30 ppm. Surface combustors are limited to processes under 1500 °F due to problems with material durability and undesirable combustion conditions (e.g., flashback, lift-off) that can occur.

Pyrocore™ Radiant Tube Burner

The Pyrocore™, a direct-fired radiant burner, was developed by Alzeta Corp. as a high-efficiency, low-NO_x burner. The device consists of a porous ceramic matrix on a 5-in. diameter metallic tube. Premixed air and gas are delivered in the center of the tube, then burn flamelessly at the outer surface of the ceramic matrix. The Pyrocore™ burner has been used successfully in several applications, including

*cf = cubic feet



(Source: GRI.)

Figure 17. Various Configurations of Radiant Tube Burner Systems.

Alzeta's advanced refinery heater, Conair Franklin's gas-fired dryer for plastic resins, Industrial Airsystems' warm-air furnace, and a Rheem commercial water heater. These applications are described in more detail in other sections of this report.

Ultra-Low-NO_x Industrial Hot-Air Burner

With support from GRI, Alzeta has developed a direct-fired gas radiant burner to take advantage of the higher thermal efficiency while operating with ultra-low emissions. The burner is based on the porous ceramic fiber material used in Alzeta's Pyrocore™ radiant burners. The NO_x emissions produced by radiant burners decrease with increasing excess air, but the Pyrocore™ burners, have been limited to 60 percent excess air due to flame lift-off from the burner surface and flame instability. The new ultra-low-NO_x burner provides flame stability at significantly higher excess-air levels by using an inward-firing burner design. The fuel/air mixture is supplied from outside the ceramic cylinder, and combustion occurs on the inner surface. Near-adiabatic* operation is required to prevent flame lift-off. Unlike the common outward-firing design, which requires a well insulated combustion chamber, inward firing does not require any insulation. In addition, the burner provides greater control of process temperatures and can be built in segments with separate fuel-air supply to provide a wide range of burner heat turndown.

The inward-firing burner maintains stable operation with over 100 percent excess air, resulting in a lower combustion temperature and much lower NO_x and CO emissions. The burner has a nominal firing capacity of 3 MBtu/h, with NO_x and CO levels of 3 ppm, and no measurable amounts of hydrocarbons.

*adiabatic: no gain or loss of heat.

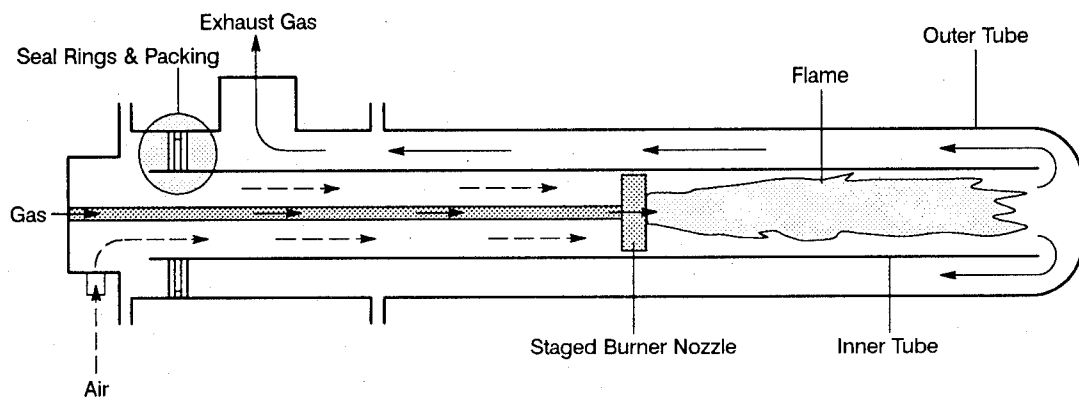


Figure 18. Single-Ended Recuperative Radiant Tube System.

The process air is delivered at 1600 °F to 2000 °F and can be lowered as far as 100 °F with dilution air. The ultra-low-NO_x burner offers a compact, low-cost, flexible alternative to conventional equipment. It is expected to be available in 1992.

Advanced Industrial Infrared Burner

Many industrial processes, such as drying food, curing plastics, and finishing ceramics depend on radiant heaters. With GRI support, Eclipse, Inc., has developed a gas-fired infrared radiant burner based on an advanced ceramic material. As shown in Figure 19, the unit consists of a nozzle, a burner housing, and a multilayered ceramic foam tile. Premixed air and gas is delivered through the nozzle and diffuses through the ceramic tile. Combustion takes place in the flame-support portion of the tile, achieving temperatures up to 2150 °F. The advanced infrared burner can produce a maximum firing rate of 200,000 Btu/h/cf, twice the rate of conventional burners with 50 percent lower pollutant emissions. The ceramic material provides a radiant heat-transfer efficiency of 45 percent, compared to 15 to 25 percent for conventional burner designs. The advanced infrared burner also provides a more uniform surface temperature, high thermal shock resistance for longer life, and a simple design to minimize manufacturing and maintenance costs.

Laboratory tests have successfully demonstrated the burner's high firing rate, excellent thermal efficiency, and low emission rate. An operating life of at least 8000 hours is projected. Field tests are currently being conducted, and the advanced infrared burner is expected to be commercially available in 1992.

Low-NO_x Burners

During the burning of fuel, NO_x emissions can originate from several sources: the oxidation of atmospheric nitrogen, high-speed reactions at the flame front, and the oxidation of nitrogen in the fuel. NO_x formation is highly temperature-dependent, and increases at higher temperatures. The main approaches used to reduce NO_x formation include reducing the concentration of free oxygen, reducing the residence time, lowering the combustion temperature, and eliminating hot spots in the combustion zone. These approaches have resulted in the development of several techniques that have demonstrated a reduction in NO_x formation. This proven technology includes high excess-air combustion, premixed gas

combustion, homogeneous combustion products, cooling of the combustion zone, and heat removal from the flame.

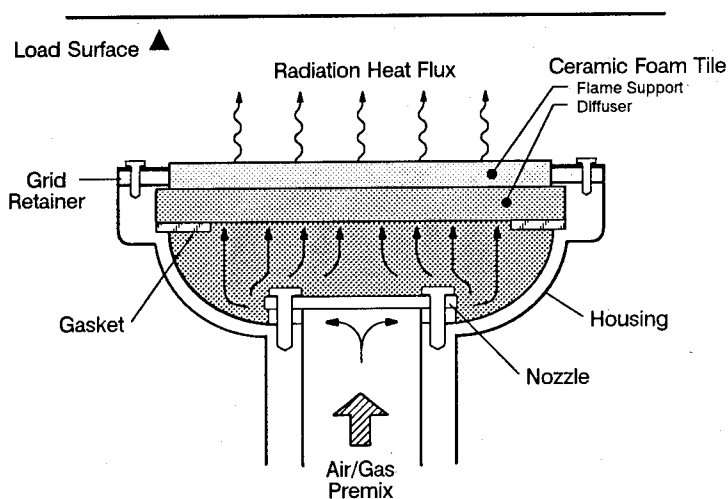
A high-performance low-NO_x burner for oil and gas designed by Arthur D. Little, Inc. (ADL), and the Massachusetts Institute of Technology (MIT) uses recirculation of flue gases and fuel-air mixing to reduce flame temperature, which in turn inhibits NO_x formation. Manufactured by Hauck Manufacturing Co., Inc., the burner incorporates some ceramic components to withstand high temperature. The research goal is an upper limit on NO_x emissions of 200 ppm at 3 percent oxygen. The burner is intended for retrofitting existing furnaces with minimal modifications of the furnace heat transfer characteristics. Field tests started in 1991.

Several low-NO_x burners for hot-air systems have been developed. The Maxon LO-NO_x Line Burner has a turndown of about 4 to 1 and NO₂ emissions of 1 ppm have been reported. Since NO₂ represents only 10 to 50 percent of total NO_x, the level of NO_x emissions is most likely 2 to 10 ppm. Urquhart has developed the CXA burner specifically for hot-air drying. The staged combustion blue-flame burner operates near 60 percent excess air and has achieved a turndown of 4:1 and NO_x levels as low as 1 to 2 ppm, but is several times more expensive than standard blue-flame combustion systems.

Industrial Furnaces and Heaters

Advanced Refinery Heater

U.S. petroleum refineries use large amounts of natural gas, with a significant amount being used by process heaters. These gas-fired process heaters have good thermal efficiencies, but produce high levels



(Source: GRI, August 1991.)

Figure 19. Diagram of the Eclipse Advanced Infrared Burner.

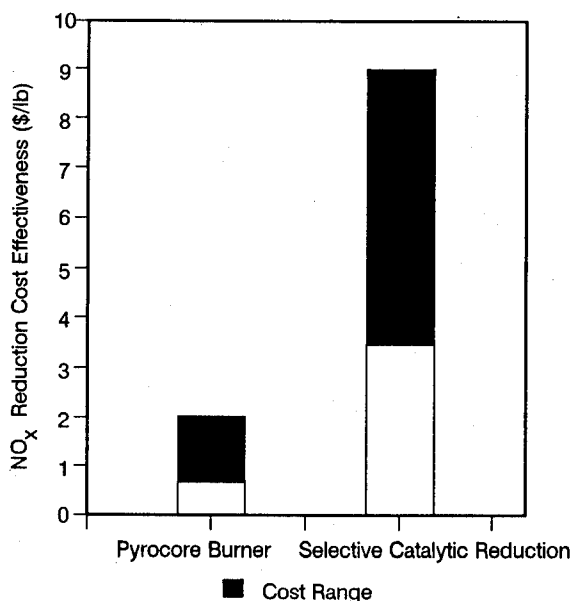
of NO_x emissions. With support from GRI, Alzeta Corp., and Kinetics Technology International Corp. (KTI) have developed a refinery heater based on the Pyrocore™ burner, a radiant ceramic fiber matrix burner. The Pyrocore was developed by Alzeta as a high-efficiency, low-NO_x burner and has been used successfully in several applications.

In the radiant burner, premixed gaseous fuel and air are passed through a porous layer of ceramic fibers and ignited on the surface, which glows uniformly at 1800 °F. Flashback is prevented by low fiber conductivity and convective cooling by the incoming fuel and air. The refinery heater contains a 10-ft radiant tube burner, constructed in two segments with a narrow, diamond-shaped cross-section. A fuel-mixture plenum within the burner controls the firing rate.

The thermal efficiency of the advanced refinery heater is expected to be greater than 85 percent. The Pyrocore burner produces less than 15 ppm NO_x. This eliminates the need for selective catalytic reduction (SCR), resulting in a significant reduction in capital costs as shown in Figure 20. The use of a radiant burner also increases productivity due to reduced fluid damage. As compared to a conventional heater (Figure 21), the refinery heater has a smaller size for reduced space requirements, and lower capital and installation costs. The refinery heater also offers instant on-off operation, negligible combustion noise, modulated heat output capability, and resistance to thermal shock. Alzeta and KTI will market the advanced refinery heater in the 80 to 200 MBtu/h size range for retrofit and new heater applications.

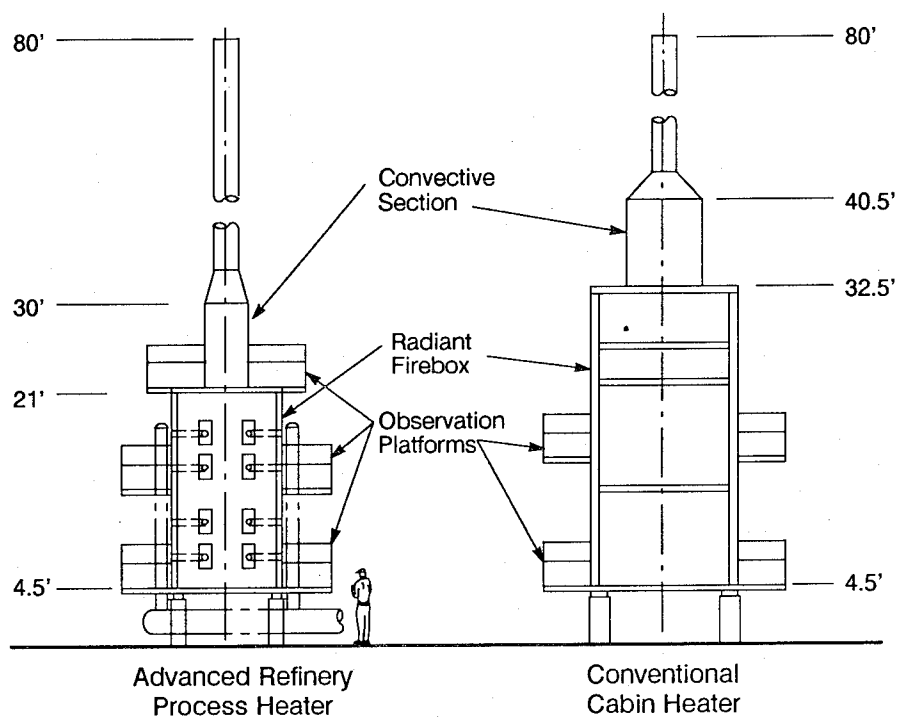
Advanced Heat-Treating Ultracase™ Furnace

The heat-treating industry has predominantly used gas-fired equipment due to low capital and operating costs. Surface Combustion, Inc., and GRI have developed an advanced batch-type, indirect-gas-fired, integral-quench furnace, as shown in Figure 22. The Ultracase™ furnaces offers high-temperature heat treating with increased productivity and efficiency.



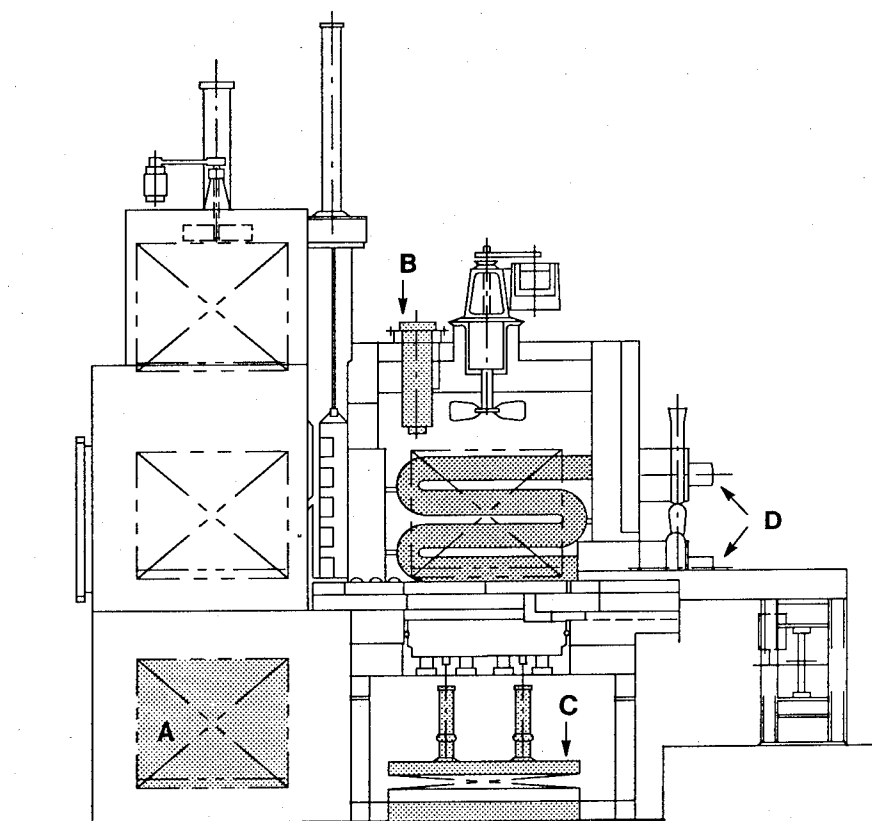
(Source: GRI, September 1987.)

Figure 20. Comparison of NO_x Reduction Costs for the Pyrocore Burner and Selective Catalytic Reduction.



(Source: GRI, September 1987.)

Figure 21. Size Comparison of Advanced Refinery Process Heater and Conventional Heaters.



(Source: GRI, June 1988.)

Figure 22. Ultracase™ Furnace.

The furnace incorporates advanced-alloy radiant tubes shaped in a "W" configuration for greater heat transfer area than conventional "U" shaped tubes. Each tube is heated by a pair of alternately firing Twin Bed™ burners developed by North American Manufacturing Co. The regenerative burners use internal heat exchangers to recover heat from the exhaust gases, improving the efficiency of the furnace. The burners also provide uniform heating, maintaining a tube-surface temperature uniformity of ± 30 °F. The uniform temperature heats the workload more consistently and also extends the life of the tubes. The advanced heat-treating furnace provides fuel savings of 50 percent over cold-air furnaces, and have a thermal efficiency of over 70 percent. The load is supported on a high-temperature, high-strength ceramic hearth bed (36 in. x 48 in. x 36 in.). During the heat-treating cycle, the load is lifted off the hearth to further reduce stress on the hearth bed. The furnace bed can handle work loads of up to 4000 lb at 1950 °F, and up to 3000 lb at 2050 °F. Alloy rollers are used to move the load in and out of the furnace.

This furnace also includes an endothermic gas generator installed inside the furnace, which can be retrofitted to existing furnaces. The gas generator provides automatic control of air/fuel ratio and delivers hot gas at 400 standard cubic feet per hour (scf/h) for normal operation (or 800 scf/h for purging). The endothermic gas generator is available as part of the advanced furnace or as a separate gas generator.

Laboratory tests of the Ultracase™ furnace were successfully completed in 1987. Field tests were conducted at FPM Heat Treating, Inc., in Elk Grove Village, IL, and at Ther-Met Processing, Inc., in Milwaukee, WI. Side-by-side comparison tests were conducted with the Allcase™ furnace, a high-efficiency conventional furnace manufactured by Surface Combustion. The Ultracase™ furnace demonstrated a 20.2 percent increase in operating efficiency at idle, and 33.4 percent higher efficiency with high-temperature workloads (2225 lb at 1700 °F).

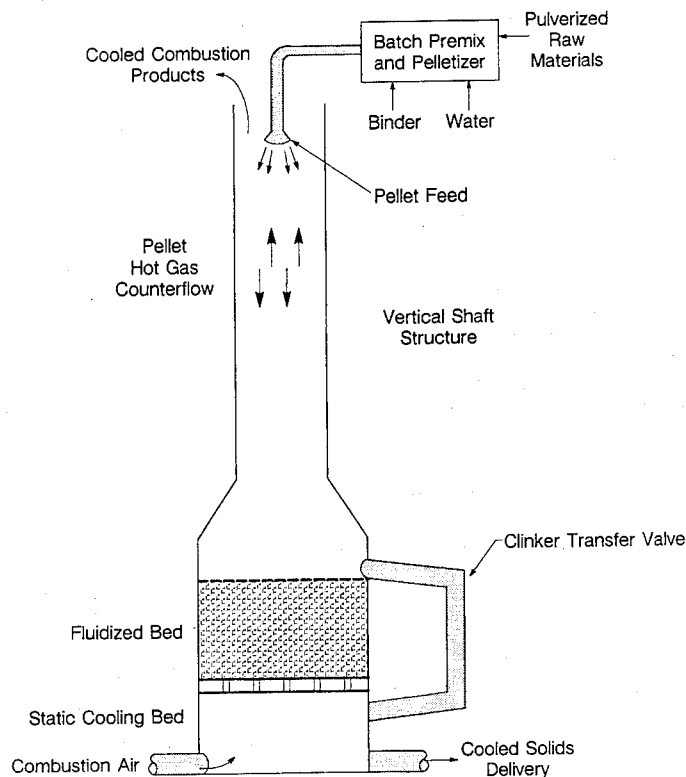
Advanced Gas-Fired Cement Furnace

Current cement production plants use large rotary kilns to complete calcining* of the limestone feedstock and produce cement "clinkers," fused particles of unground raw product. A coal-fired rotary kiln requires high capital, operating, and maintenance costs. Textron Defense Systems, sponsored by GRI and the Southern California Gas Co., have developed a gas-fueled cement advanced furnace (CAF) to reduce costs and comply with increasing environmental regulations.

In the CAF, the horizontal rotary kiln is replaced by a vertical suspension shaft and fluidized bed. The design incorporates Textron's advanced gas suspension process with Fuller Co.'s fluidized bed process. As seen in Figure 23, pellets of raw materials enter at the top of the suspension shaft and are preheated. The pellets are partially calcinated as they fall through the rising combustion gases, which takes only a few seconds. The flow of pellets and the counterflow of hot gases are balanced for increased residence time. The calcination and clinkering reactions are completed in the fluidized bed. The bed remains at a constant temperature, which is critical for product quality. In the cooler beneath the fluidized bed, the clinkered pellets are cooled by air, which is then used to preheat air for combustion. The cooled solids are then ground to produce powdered cement.

The CAF has many advantages over the rotary kiln design. The gas-fired furnace produces significantly lower CO₂, NO_x, and SO₂ emissions, and eliminates the cost of coal handling and processing. The CAF design provides a 10 percent increase in thermal efficiency, and processing time is reduced from hours to minutes, resulting in a 10 percent lower production cost. Installation costs are 15 percent lower than for the conventional rotary kiln design, and maintenance costs are also reduced because there are

*calcining: to heat under oxidizing conditions.



(Source: GRI, January 1992.)

Figure 23. Fuller Cement Advanced Furnace.

fewer moving parts. Finally, the design of the CAF allows for easier expansion, and can be used as a retrofit for the modernization of existing plants.

Analytical and experimental work on the furnace was conducted by Textron, and the experimental testing on the pilot plant was performed at Fuller's research and development (R&D) facility. Preliminary results were successful, and Fuller was scheduled to begin marketing the cement advanced furnace in 1992.

Blast Furnace Natural Gas Injection

Conventional blast furnaces used for reducing iron ore to pig iron or "hot metal" are usually fueled by metallurgical coke. With growing regulation of environmental effects, the use of coke in existing furnaces is becoming more expensive due to high levels of emissions. In addition, improving the performance and productivity of existing furnaces has proven to be more cost effective due to the high capital costs of installing new equipment. For the past 30 years, cofiring with natural gas, oil, or tar/pitch has allowed a small reduction in the amount of coke consumed. A recent study by Charles River Associates, a consulting firm, reported that increased natural gas injection has a great potential for improving productivity and reducing emissions from coke ovens. With support from GRI and members of the steel industry, Charles River Associates is developing the technology and conducting field tests to demonstrate the benefits of increased natural gas injection.

In a blast furnace, pellets of iron ore, coke, and other materials are delivered to the top of the furnace. These pellets are subjected to a hot blast of pressurized air and steam rising to the top of the furnace in a counter flow direction. The coke reacts with the hot blast and forms CO and hydrogen, which reduce iron ore to molten iron and slag. Natural gas injection provides additional hydrogen, which is more

efficient than CO in reducing ore at high temperatures. Oxygen, injected with the natural gas, maintains the furnace temperature.

Increasing natural gas injection can improve productivity, reduce emissions, and provide flexibility for blast furnaces at a relatively low capital cost. The goal of the gas-injection project is to inject up to four times the amount of natural gas currently used. Each pound of natural gas would replace 1.3 lb of coke. Estimates predict a 10 percent increase in productivity, which would result in an annual savings of \$18 million for a 4000 tpd blast furnace. Emission reductions of 25 percent or more are expected to be proportional to the amount of coke replaced. Natural gas injection also provides more flexibility for the furnace to follow the rising and falling of steel demand. Unlike coal and coke, natural gas contains no sulfur, and this results in better hot metal quality. As compared to cofiring with oil and coal, the use of natural gas injection involves lower capital costs, lower maintenance costs, lower slag loads, and less need to treat hot metal for desulfurization.

Production-scale tests began in 1991 with a gas-injection rate of 150 lb, which reduced coke consumption by 20 percent and increased iron production by 8 percent. The final results of the natural gas injection demonstration will be computed by Charles River Associates and GRI, and are expected to be available in 1992.

Gas-Fired Ion-Nitriding Vacuum Furnace

While 74 percent of the energy used to heat-treat metals is supplied by natural gas, the only vacuum furnaces commercially available are electric. A vacuum furnace offers many advantages, including low emissions, flexibility, and protection of the metal surface. With support from the GRI and Southern California Gas Co., Abar Ipsen Industries, and Indugas, Inc., have developed a gas-fired vacuum furnace for ion-nitriding applications. Ion-nitriding is a process in which nitrogen ions react with the steel surface to form nitrides that produce a hardened outer layer, which improves wear and fatigue resistance of the steel.

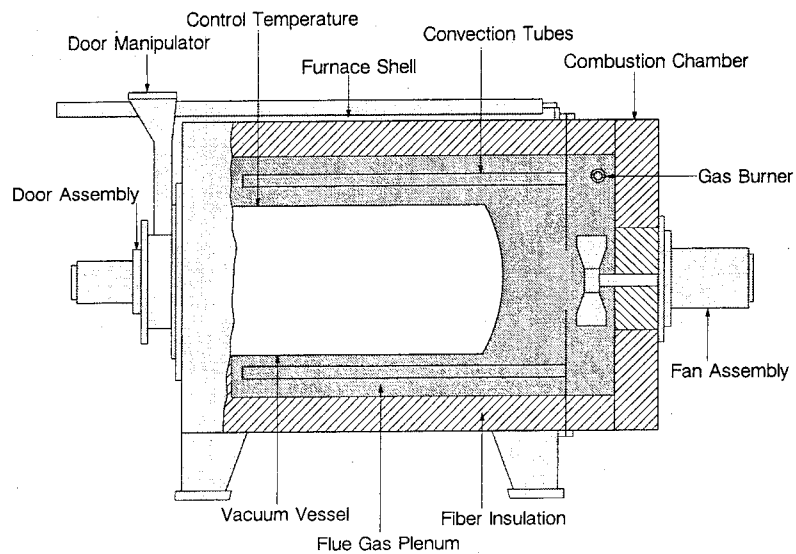
The gas-fired ion-nitriding vacuum furnace consists of a cylindrical alloy vacuum vessel within an insulated furnace, as shown in Figure 24. Two burners are fired tangentially with a stoichiometric fuel-air mixture at high-heat demand and excess air at low-heat demand. The hot combustion gases are mixed with recirculating flue gases and pressurized. The pressurized hot gases are directed into uniformly spaced jets that directly contact the vacuum vessel, heating the vessel walls to high temperatures in a very short time. A fan-pressurized recirculating system maintains uniform heat fluxes, as illustrated in Figure 25.

Inside the vessel, an internal convection fan housed in the vacuum door produces convection currents for rapid heating and cooling. At lower temperatures, the vessel is filled with nitrogen to prevent oxidation and the heat is transferred to the metal by convection. At high temperatures, the metal is heated via radiation.

Temperature uniformity and control are critical in heat treating processes. The gas-fired vacuum furnace provides better temperature control, resulting in improved temperature uniformity. The gas furnace also offers shorter heating times, increasing productivity through reduced energy and operating costs. The gas-fired vacuum furnace also has a lower capital cost than electric versions.

In laboratory tests, temperature uniformity of the gas-fired vacuum furnace was less than half the temperature spread in electric units. The tests reported a temperature uniformity of ± 7.5 °F in the vacuum vessel at 1000 °F and atmospheric pressure, and only ± 3.5 °F at 1250 °F under vacuum (0.01 torr). The maximum gas input is 1.5 MBtu/h and maximum load temperature is 1250 °F. The net load is 1200 lb and the load size is 24 in. wide, 36 in. long, and 18 in. high. Abar Ipsen is working to offer the ion nitriders commercially.

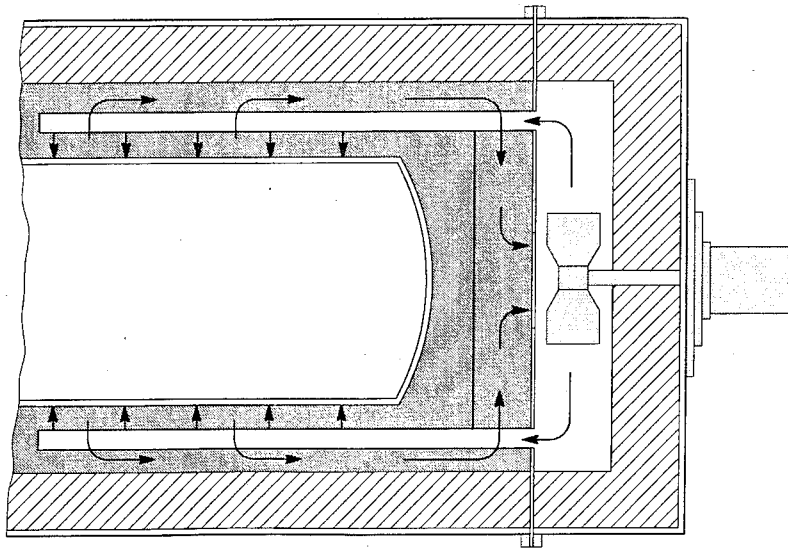
GAS-FIRED ION NITRIDER, SIDE VIEW



(Source: AGA, Summer 1991.)

Figure 24. Gas-Fired Ion Nitriders.

RECIRCULATION LOOP



(Source: AGA, Summer 1991.)

Figure 25. Recirculation Pattern Provides Uniform Heat Fluxes.

The same concepts can be applied to high-temperature processes (up to 1750 °F) used for applications such as tempering, stress-relieving, normalizing, annealing, and carburizing. The high-temperature gas-fired vacuum furnace is currently being field tested.

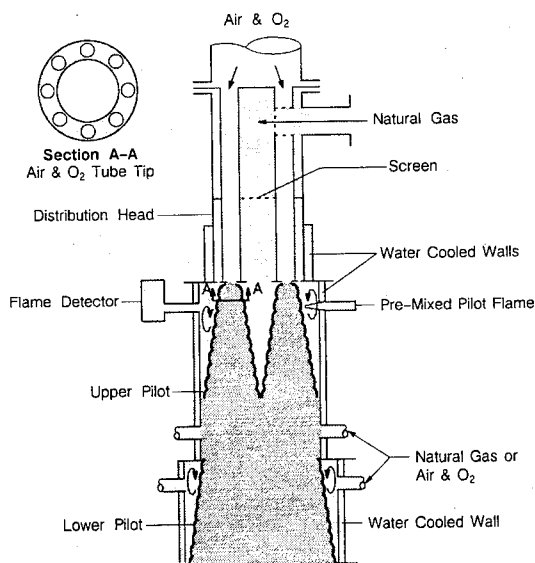
Gas-Fired Electric Arc Furnace Dust Incineration Process

Electric arc furnaces (EAF) used for scrap steel produce large amounts of dust containing toxic materials. USEPA has classified EAF dust as hazardous solid waste. A coal-fueled Flame Reactor™ can be used to incinerate the dust, but is only cost-effective for large-scale plants due to cost of handling and processing the coal. GRI and Horsehead Resource Development Company, Inc., have developed a gas-fired high-temperature flash-smelting burner for onsite use for smaller steel mills.

As illustrated in Figure 26, the gas-fired Flame Reactor™ consists of a vertical reaction chamber divided into a burner stage with a reactor stage below it. The walls of the chamber are watercooled. Natural gas is combined with oxygen-enriched air and ignited in the high-temperature (over 4500 °F) burner section. In the reactor stage, EAF dust is injected into the reducing gases. Most of the molten slag flows down the chamber wall into a gas-liquid separator. The resulting slag is drawn off and the gases are combusted with air to reoxidize and condense the volatile metals. The zinc-, lead-, and cadmium-rich crude oxide is recovered in a baghouse and sold as feedstock to the zinc industry. The chromium is neutralized in the slag.

The burner was designed under subcontract by Sverdrup Technology, Inc. The net cost of the gas-fired unit is estimated at \$100 to \$200 per ton of dust. Compared to coal delivered at \$50/ton, the break-even cost of gas for a 10,000 ton/year system would be about \$3.90 per thousand cubic feet (mcf). Tests conducted on a 30 MBtu/h burner produced a 98 percent process efficiency over a 4-to-1 turndown

HRD FLAME REACTOR Process Gas Fired Combustion



(Source: GRI, November 1990.)

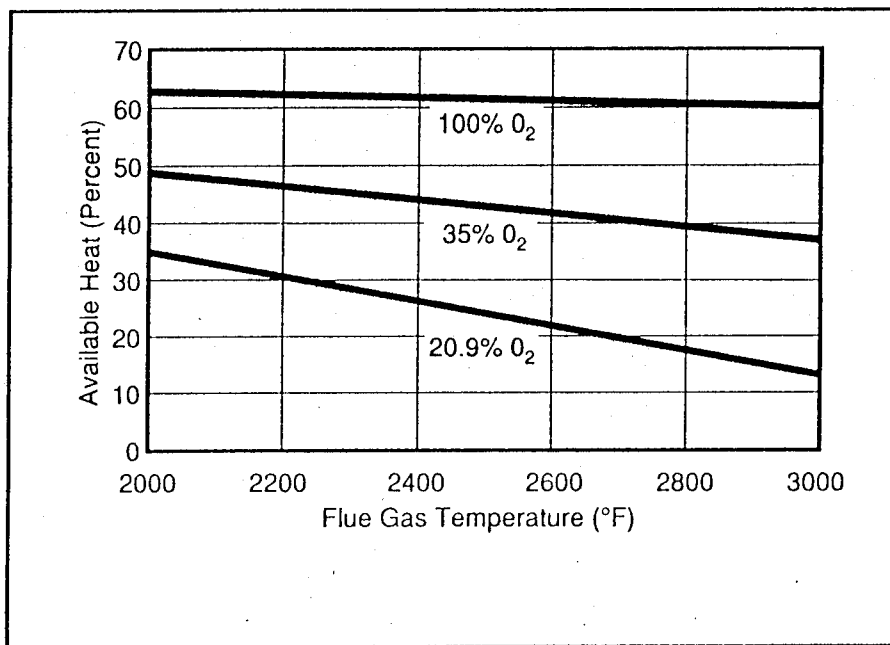
Figure 26. Gas-Fired Combustor for the Flame Reactor™.

ratio. In field tests of dust from five different plants conducted under various operating conditions, salable products, such as zinc, lead, and cadmium, were recovered (and sold to the zinc industry) and slag and air-emissions standards were met. Currently, the gas-fired Flame-Reactor™ is being developed for two commercial plants with capacities of 20,000 tons/yr and 13,000 tons/yr.

Oxygen Enrichment for Furnaces

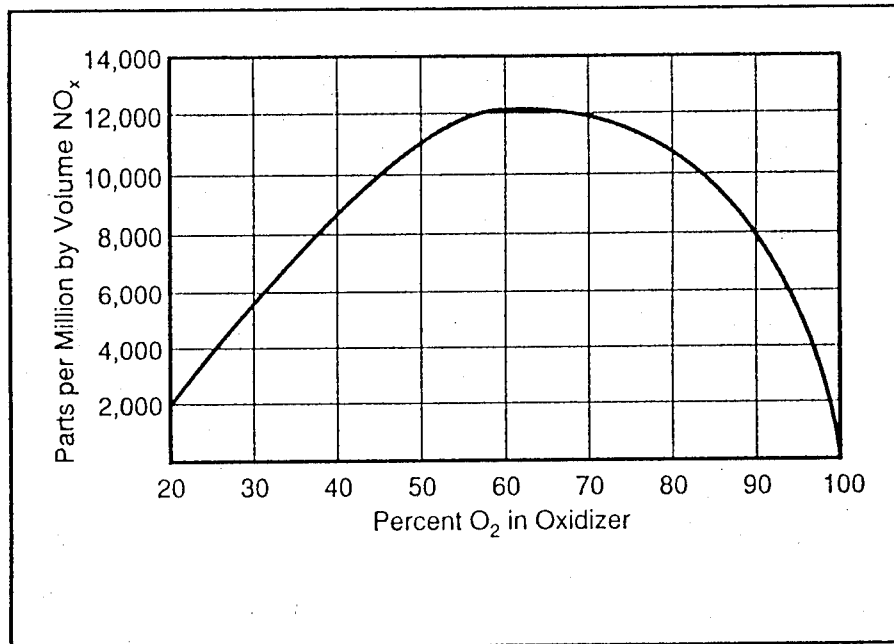
Oxygen enrichment is a technique for improving the efficiency of gas-fired furnaces and reducing emissions by increasing the amount of oxygen supplied to the burner. Air consists of about 21 percent oxygen and 79 percent nitrogen by volume. In conventional air/fuel combustion, only the oxygen is consumed. Nitrogen, which is inert, acts as a diluent, absorbing the heat of combustion and carrying it out with the exhaust gases. Increasing the amount of oxygen in combustion significantly increases flame temperature because less energy is required to heat the remaining nitrogen. The increase in flame temperature produces a corresponding increase in furnace productivity and efficiency. Figure 27 shows the relationship between oxygen-enrichment and increased available heat.

Although higher combustion temperatures generally accelerate thermal NO_x production, this increase is offset by the reduced amount of nitrogen available in the system. The relationship between oxygen-enriched combustion and NO_x emissions is shown in Figure 28. Oxygen-enriched combustion can also reduce particulate emissions because of the lower gas volume consumed. In addition, the higher flame temperature in this system produces fewer unburned hydrocarbons. With the increased efficiency of the furnace, a lower flue-gas volume is required, so smaller fans, ducts, and gas-treatment equipment can be used. The burner should be custom-tailored to the application and properly located to avoid damage caused by furnace hot spots resulting from higher flame temperatures.



(Source: Baukal, Eleazer, and Farmer, February 1992.)

Figure 27. Relationship Between Available Heat and Oxygen-Enriched Combustion.



(Source: Baukal, Eleazer, and Farmer, February 1992.)

Figure 28. Relationship Between NO_x Levels and Oxygen-Enriched Combustion.

In the late 1980s, Air Products with Peoples Natural Gas converted a gas-fired furnace to oxygen enrichment for glass melting at Glenshaw Glass. The conversion was successful and reduced electric costs by 40 percent, producing a net savings of over \$150,000 annually and increasing productivity.

Air Products is also using oxygen enrichment in the development of a steel reheat furnace to provide increased efficiency, flexibility, and reliability over conventional reheat furnaces. The reheat furnace incorporates the design of a unique burner patented by Air Products and Nordsea Gas Technology Ltd. of the United Kingdom. The burner produces low velocity, high temperature flames that directly heat the steel. Computerized controls continuously monitor the steel temperature and adjust the heating rate to avoid overheating. Bench-scale tests achieved a heating rate of 200 °F per minute which will reduce initial furnace heat up by 10 to 50 percent, enable quick shutdowns and increase flexibility. The savings in fuel due to improved efficiency and the increase in metal yields far outweigh the cost of using oxygen. A prototype of the reheat furnace is currently being field tested.

Gas-Fired Rapid-Heating Furnace

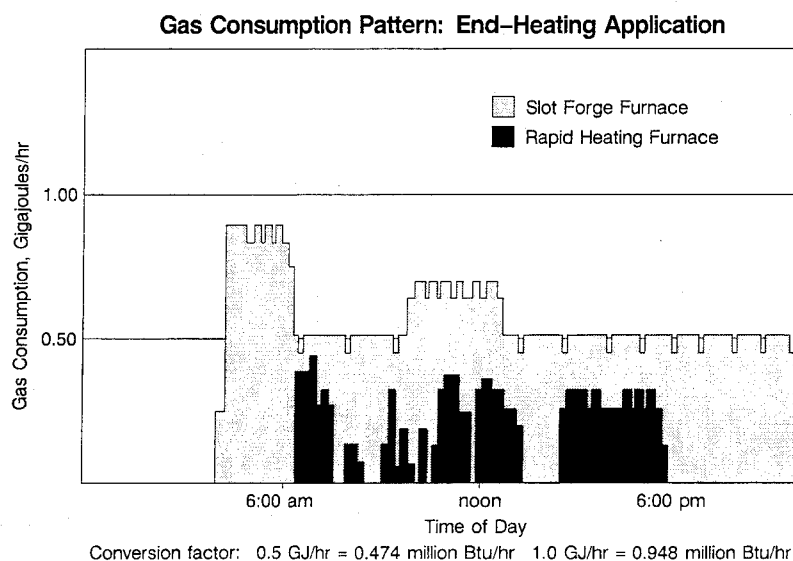
Gas-fired rapid-heating was developed by British Gas in the 1960s, and has been successfully used for metal reheating in Europe and the United States, primarily in the spring-making industry. Gas-fired rapid heating has many advantages, including higher efficiency, lower capital and operating costs, and improved product quality. This technology is currently being expanded for other metal reheating applications.

The gas-fired rapid-heating furnace design increases heat transfer by adding convective heat through a stream of combustion gases to the conventional radiant heat from the furnace refractory wall. About 60 to 70 percent of the heat transfer to the load is convective. The internal shape of the furnace is

designed to match the shape of the workpiece, therefore high gas velocities can be directed over a large portion of the workpiece surface. The heat transfer can be controlled by increasing or decreasing the velocity of the hot gases. In addition, stock temperature rather than the furnace temperature is monitored to provide better temperature control, thus improving product quality by eliminating the risk of overheating.

The rapid-heating furnace also uses a recuperative design to further increase its efficiency. As the parts move toward the burners, located at one end of the furnace, the combustion gases flow in the opposite direction, toward the moving parts. This preheats the incoming parts with the combustion gases.

Gas-fired rapid heating provides many benefits in metal reheating applications. The rapid-heating furnace offers quick startup, reaching 2400 °F in a few minutes making it cost- and time-effective to shut off the furnace or switch it to low fire when not in use, then restart it within a few minutes for full production. Figure 29 illustrates the daily gas consumption pattern of a rapid-heating furnace as compared to a slot-forge furnace. The combination of quick startup and high efficiency provides fuel savings of 40 to 70 percent, compared to conventional furnaces. Rapid heating improves product quality by heating the metals quickly and minimizing the time above scaling temperature, thus reducing scaling and decarburization. The temperature of work pieces is monitored and controlled so they are not overheated, and this eliminates deformation problems. Rapid heating also increases productivity by as much as 40 percent. The furnace also is compatible with the automated loading, unloading, and conveying of stock. The environmental heat loss of the furnace is minimal, resulting in better working comfort and lower worker fatigue.



(Source: AGA, Fall 1991.)

Figure 29. Gas Consumption Pattern of a Rapid-Heating Furnace.

The rapid-heating furnace has low maintenance and operating costs, and is usually less expensive to purchase and install than a comparable electric induction heating furnace. In addition, the use of natural gas instead of electricity reduces energy costs and peak demand charges.

Rapid-heating technology furnaces were marketed in Europe and the United States during the 1970s and 1980s. Triangle Auto Spring, a leaf spring manufacturer in Columbia, TN, purchased two rapid-heating furnaces in 1986. Installations costs were one-third lower than for conventional furnaces, and the equipment required less maintenance. In operation, the front-fired furnace had a 59 percent fuel savings and production was increased by 40 percent. Following this success, Triangle purchased additional newer models which achieved fuel savings of 64 percent with a 35 percent gain in productivity over conventional equipment ("Expanded Applications for Gas-Fired Rapid Heating" 1991).

Rapid Technologies was formed in 1990 with an international license from British Gas to manufacture and sell rapid-heating technology in North America. Rapid Technologies can customize gas-fired rapid-heating systems for any metal reheating application. The product line includes a portable unit (30 in. x 18 in.) with a thermal capacity of 135 cf/h and a maximum temperature of 2000 °F.

Industrial Glass Applications

DOD requires a wide variety of glass components for military vehicles, vessels, and aircraft. Many of these are specialty items that could benefit from the improved quality control available from emerging natural gas technologies and lower energy consumption.

Cullet Preheater

A common goal for glass manufacturers is to lower production costs and reduce melting furnace emissions. Increasing the firing rate of the burner to increase production is limited by the burner capacity and the furnace refractory temperature ratings. A higher firing rate can also lead to increased emissions. The addition of electric-resistance heating or oxygen-gas firing does not increase emissions but can significantly increase production costs. To improve the productivity of glass furnaces at a low cost without increasing emissions, a gas-fired system to preheat cullet (crushed recycled glass) was developed by Tecogen, Inc., with support from GRI and Southern California Gas Co. The system preheats cullet before adding it to the furnace with the rest of the glass batch raw materials. The addition of energy to the furnace, in the form of hot cullet, increases the energy efficiency of glass production.

The cullet preheater is a direct-contact counterflow heat exchanger (Figure 30). Cullet is delivered at the top of the system and is heated as it falls through the hot combustion gases rising from the gas-fired burners at the bottom. The cullet is heated to 1150 °F, the temperature at which it softens and begins sticking together. It is then discharged from the preheater and fed to the furnace charger. Cullet fines (small particles) carried by the exhaust gas are captured and added to the preheater discharge. The efficiency of the system can be increased by recirculating the preheater exhaust gases. The additional energy provided by the preheated cullet increases glass production of the furnace while maintaining the existing firing rate. The low operating temperature of the cullet preheater generates negligible NO_x. Thus, the increase in production of the system results in an overall reduction in emissions per production unit. The graphs in Figure 31 show the projected effect of cullet preheating on the production increase and NO_x reduction. In addition, the unit can be installed as a retrofit without interrupting furnace operation.

The cullet preheater is being marketed by Tecogen, Inc., under the name Tecullet™ preheater. Although the increase in production resulting from the cullet preheater will vary with the installation, payback for the installed cost of the unit is projected to range from 6 months to 2 years.

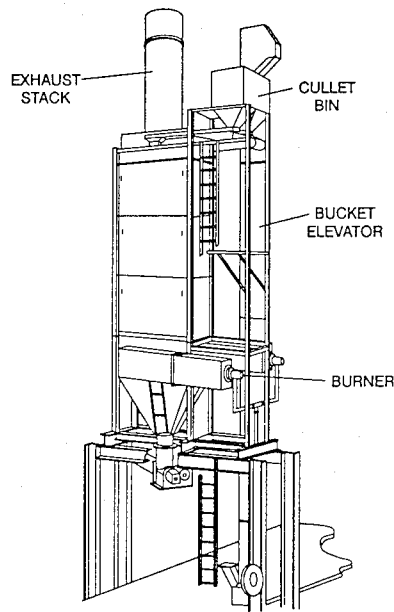


Figure 30. The Tecullet™ Preheater System.

Glass Batch Preheater

Due to the increase in environmental regulation, glass manufacturers have been required to install expensive pollution-control equipment or electric furnaces. Many pollution-control devices reduce emissions by lowering the furnace firing rate, but this also reduces the production rate. The use of all-electric furnaces and electric "boost" preheaters can maintain or improve production, but they also significantly increase operating costs. Thermo Electron Corp., with GRI and Southern California Gas Co., has developed a new gas-fired technology for preheating raw glass materials to improve productivity and reduce emission levels.

Shown in Figure 32, a fluidized bed is used to preheat loose batch material such as silica sand, limestone, dolomite, soda ash, borates, and feldspar. The heat supplied to the bed is recovered from the melting-furnace flue gases to improve overall efficiency. The batch is suspended in a current of hot flue gases rising through a perforated plate. Due to the close contact between the particles in the batch and the hot gases, the fluidized bed acts as an extremely efficient heat exchanger. In addition, particulates are captured by the bed and returned to the furnace. This not only recovers material that can be used in the glass product, but it also eliminates the need for expensive pollution-control systems such as an electrostatic precipitator or baghouse. To assure uniform gas distribution, a water spray system is used to remove deposits that might accumulate and block the perforations in the distributor plate.

The preheater is projected to improve productivity by 25 percent at a fixed gas-flow rate. This not only provides fuel savings but also lowers emission levels produced per production unit. With the batch preheater, NO_x and particulate emissions are estimated at 4 lb/ton and 0.25 lb/ton, respectively. The capital cost of the batch preheater is estimated at \$800,000, with a projected annual operating cost of \$500,000.

The preheater can be installed without interrupting glass production, and is compatible with container or flat glass furnaces (end port or side port). It can also be used in combination with other advanced technologies such as oxygen enrichment. The glass batch preheater is marketed by Toledo Engineering.

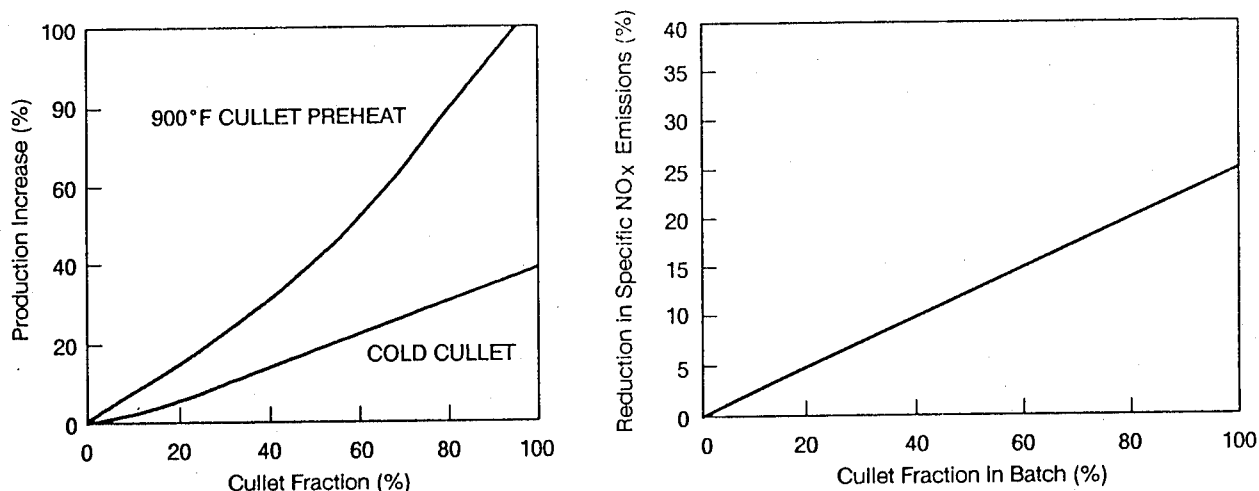
Advanced Glass Melter

In order for glass manufacturers to be competitive, new technology is needed to provide furnaces with high efficiency and high productivity, while meeting environmental regulations. While electric furnaces reduce emissions, gas-fired furnaces provide higher productivity at a lower cost. Avco Research Laboratory, Inc., with support by GRI, has developed a gas-fired advanced glass melter (AGM).

The AGM design varies significantly from conventional open-hearth furnaces. Fine particles of glass batch materials are premixed and injected into a high-temperature preheated-combustion-air stream, and transported to a high-intensity combustion zone. Residence time in the combustion zone is less than 50 milliseconds (insec), and the resultant quenching of the combustion gases by the inert batch materials inhibits NO_x formation. Below the combustion zone is a melt separation chamber, in which the hot materials are separated from the combustion gas and deposited on a collecting surface, where the glass-forming reactions take place. The shear forces of the gas on the solid materials produces rapid mixing and bubbling, which eliminates the need for the sulfate additives used in conventional furnaces that produce SO_x emissions. The glass then flows to the bottom of the chamber, where additional homogenization occurs before it flows out of the chamber to glass-forming equipment. The exhaust gases flow out the exhaust ports and are then directed to a heat-recovery system.

The smaller furnace size of the AGM results in lower capital costs than conventional furnaces. Operating costs should also be lower due to lower maintenance requirements, fast product turnaround capability, and a reduction in the time needed to change product color. The AGM design can be used for new facilities or retrofit applications.

The AGM has successfully been tested in the laboratory, and further tests are being conducted. A cost analysis was performed comparing the AGM to a conventional electric furnace. A fuel savings of \$3.90 to \$8.00 per ton of glass was predicted for AGM retrofits, depending on the type of product and furnace size. A comparison of a new AGM system with a new conventional facility resulted in a predicted fuel savings of \$5.50 to \$8.30 per ton.



(Source: GRI, November 1990.)

Figure 31. Graphs Illustrating Production and Emission Improvements Offered by Cullet Preheater.

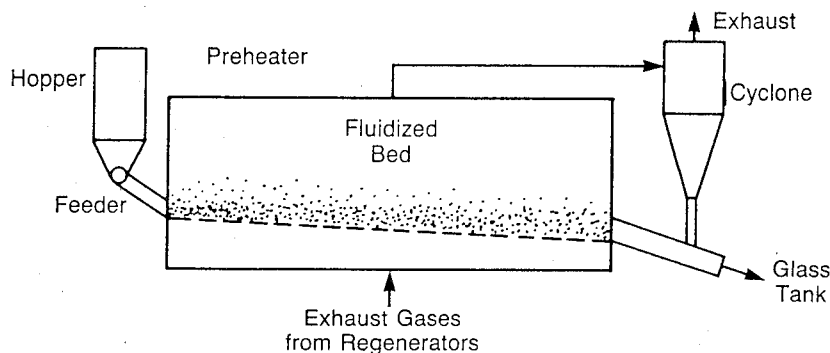


Figure 32. Fluidized Bed Used for the Glass Batch Preheater.

Mineral Wool Melter

Mineral wool is currently produced in coke-fired cupolas.* A mixture of basalt rock, blast-furnace slag, mineral additives, and coke is melted in the cupola, then spun into fibers. To meet current and future emission regulations, expensive pollution-control equipment will be required. Improvements in energy consumption, product quality, and process efficiency are also important. GRI and A.C. Leadbetter & Son, Inc., have developed the GASWOOL Melter™ to address these issues. Indugas, Inc., and U.S. Mineral Products also participated in the project.

The GASWOOL Melter™ has separate melter and forehearth sections. In the melter section, gas burners mounted in the walls are fired tangentially, and maintain a temperature of approximately 2750 °F. The heat from the flue exhaust is recovered and used to preheat the combustion air. The rock and slag charge collects in the melter in a conical pile, melts on the surface, then flows to the melter hearth. The melt then flows to the forehearth, where the temperature is increased for fiber production. The forehearth improves temperature uniformity and controllability of melt viscosity. Excess-air firing in both sections avoids the formation of CO and combustibles, and maintains maximum flame temperature.

The GASWOOL Melter™ virtually eliminates CO and unburned hydrocarbon emissions and substantially reduces SOx and NOx. Process wastes are recycled to avoid the cost of waste disposal and improve productivity. The gas-fired melter also provides more precise control of melt temperatures and flow rate, which influences the quality of the glass fiber. The GASWOOL Melter™ is projected to use only 60 to 70 percent of the fuel used by a coke-fired cupola. In addition, the melter's energy cost of \$18.00 per ton of melt is much lower than the coke-fired cupola costs of \$28.40 per ton of melt. Although the capital cost is higher, the lower operating cost of the GASWOOL Melter™ results in a payback of less than 2 years (Freeman and Blazek June 1992). The GASWOOL Melter™ became commercially available in 1991.

*cupola: vertical cylindrical furnace.

Industrial Dryers

Pulse Combustion Dryer

Spray dryers are commonly used to dry pumpable slurries or solutions. Existing spray dryers have a number of problems, including possible degradation of heat-sensitive products, low energy efficiency, large size, and rapid wear of nozzles and rotary atomizers. Bepex Corporation and GRI have developed a gas-fired industrial dryer based on a high-pressure pulse combustion burner. The dryer, marketed under the name Unison™, is designed to efficiently dry moderately temperature-sensitive and nontemperature-sensitive materials such as polymers, minerals, clays, and calcium carbonate.

The Bepex dryer, shown in Figure 33, consists of a pulse combustion burner and drying chamber. The pulsed-combustion air is delivered at a rate of about 150 Hertz (Hz). Combustion is initiated by a pilot flame that is turned off as the combustion pulses become self-sustaining, producing high amplitude

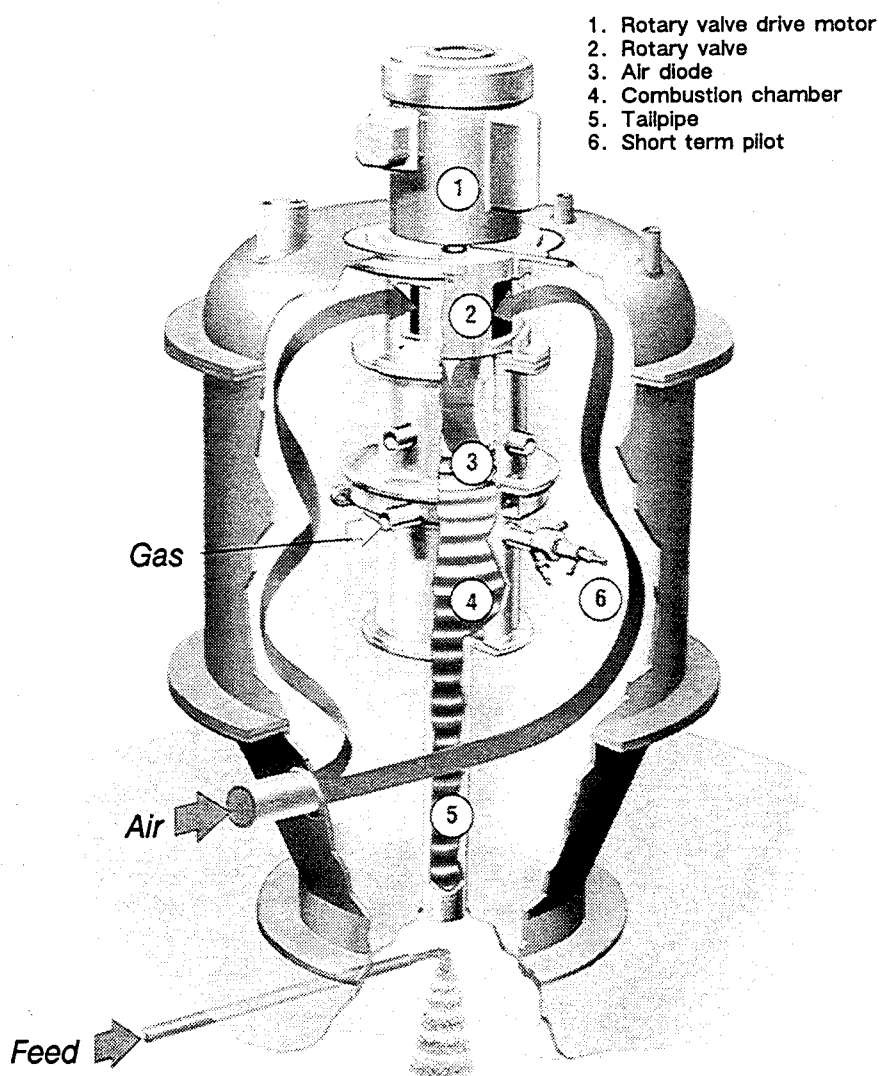


Figure 33. The Unison™ Dryer.

sonic pulsations up to 180 decibels adjusted (dBa). Air and exhaust gases enter the drying chamber at 1000 to 2000 °F. The drying air outlet temperatures range from 180 to 250 °F, and the product outlet temperatures are typically 120 to 140 °F. The residence time of the material in the hot zone of the drying chamber is less than 5 msec. The dried product is then collected in a cyclone or bag filter. An outlet silencer is used to keep external sound levels below levels prescribed by the U.S. Occupational Safety and Health Administration (OSHA).

The pulse combustion dryer has many advantages over conventional spray dryers and a lower installed cost. The increased mass and heat transfer allows for shorter residence times and low heat input, which results in better product quality, reduced production costs, and lower stack gas volume. In addition, high-temperature construction materials and the lack of exposed moving parts reduce maintenance requirements and increase the operating life of the dryer.

In pilot tests, the Unison™ has evaporated up to 600 lb/hr of water using 1200 to 1400 Btu/lb of water removed, and slurries containing up to 90 percent solids can be handled. The Unison™ was first introduced by Bepex in 1991.

Convective Microwave Industrial Dryer

Food drying requires carefully controlled heating to prevent overcooking the food, and effective monitoring to control bacteria growth. Energy International, Inc., and GRI have developed a dryer that uses both convective heat and microwave or radio-frequency energy. The microGas™ is designed to provide the optimal balance of food quality and operating costs.

The microGas™ system is based on a 30 kW gas-fired engine that drives a generator to provide electricity for the microwave generator. The system is illustrated in Figure 34. The convective heat is provided by auxiliary gas burners and engine heat recovery. Of the fuel consumed by the unit, 25.7 percent is converted to electricity and 55 percent is recovered for drying. In the microGas™ dryer, 97 percent of the drying is supplied by the convective heat from the gas burners. The microwave energy is useful for the latter stages of finish drying, to remove the last moisture. Microwave energy generates heat throughout the material, thus avoiding high surface temperatures and minimizing energy losses from heating the surrounding air. The microGas™ system improves product quality and drying speed.

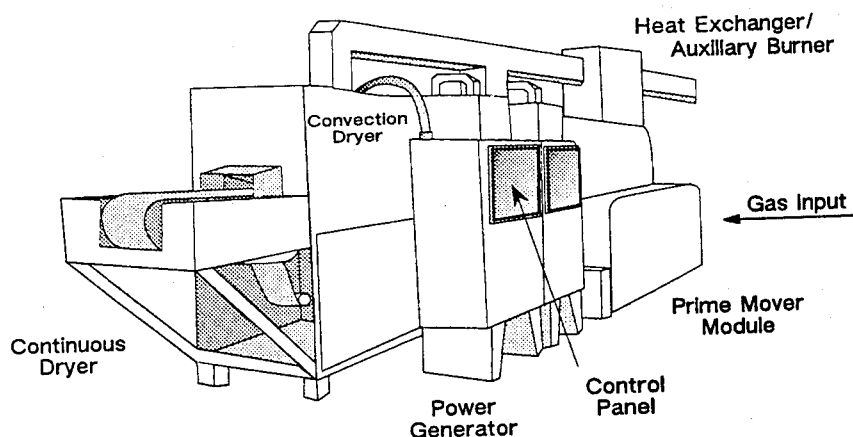


Figure 34. MicroGas™ Dryer System.

In recent field experiments, the microGas™ dryer completed the target goal in one-fourth the time required by conventional convective-heat systems. This system not only improves productivity, but also gives bacteria less time to grow, potentially eliminating the need for chemical fumigation. Payback of the system is estimated at 2 years. The microGas™ can also be used in the processing of rubber, chemicals, textiles, and forest products. Energy International and Burnett Oil Company of Fort Worth, TX, have formed a joint venture to produce and market the microGas™ system.

Dryers for Plastic Resins

In the U.S. plastics industry, the drying of plastic resins must be carefully controlled before molding or extrusion to ensure product quality. Currently, electric dryers are used to heat the resins and regenerate the desiccant cartridges. GRI, Conair Franklin, Alzeta Corp., and Texas Gas Transmission Corp. have developed a gas-fired dryer to provide excellent temperature control at lower energy costs.

Compu-Dry Gas (CDG) series dryers consist of Alzeta's Pyrocore™ ceramic-fiber-matrix radiant burner, with advanced compact heat exchange, air-fuel train, and burner control system. The Pyrocore™ burner provides flameless combustion, high radiant heat flux, uniform heat transfer, variable surface geometry, and fast thermal output response. The CDG dryer contains two heat exchangers—one for heating the process air and one for regenerating the desiccant cartridges. The first model produced, the CDG 400, delivered 300 cf/min (cfm) of process air, ranging from 160 to 375 °F and 73 cfm to regenerate the desiccant at 425 °F. The variable-firing-rate control system maintains the temperature for process air within ± 1 °F and for regeneration within ± 5 °F.

The CDG is expected to reduce energy costs 50 to 70 percent, compared to electric dryers. Although the initial cost of the CDG projected to be 30 to 40 percent higher than for electric equipment, the lower energy costs and the reduction of electric peak load charges results in an estimated payback period of 6 months ("Gas-Fired Dryers for Plastic Resins" August 1989). In addition to the CDG 400, dryer models with higher airflow rates available include the CDG 600, CDG 800, CDG 1000, CDG 1600, and CDG 2400.

Industrial Compressors

An increasing variety of tools and machinery are being run on compressed air. Although most industrial compressed air systems are driven by electric motors, gas-fueled engines provide a low-cost, high-efficiency alternative.

Although electric rates vary from region to region, the energy cost of operating a gas-fueled engine is usually much lower than the cost of operating an electric motor. In addition, the variable speed capability of gas engines allows them to operate efficiently at partial load. An example of this would be a rotary screw air compressor, a positive displacement machine in which output varies with speed. At lower speeds, it produces less air and consumes less energy, so it maintains high efficiency at a wide range of speeds. Therefore, regulating engine speed can effectively control compressor output. Electric compressor motors, on the other hand, are constant-speed devices without the flexibility of gas engines. The output capacity of electric compressors is controlled by throttling (restricting) the compressor inlet, which inherently reduces efficiency. Also, gas-powered compressors reduce costs by eliminating peak electric demand charges and freeing up electric capacity.

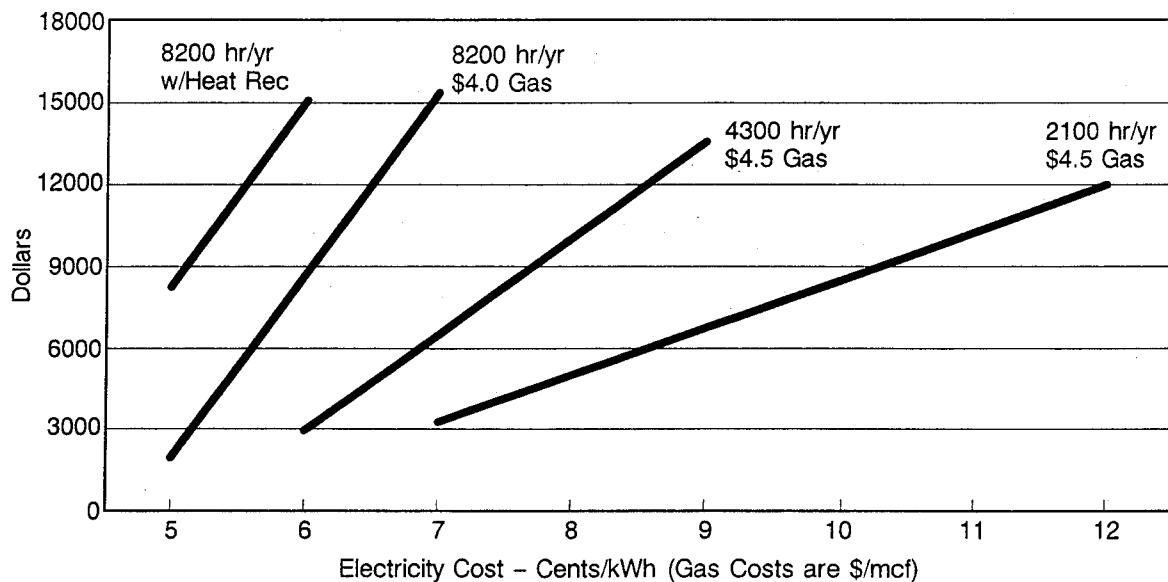
Because natural-gas engines produce significant amounts of heat, the recovery of waste heat can further improve the compressor's operating efficiency. The waste heat can be used for space heating, preheating boiler feed water or combustion air, or for hot water or drying applications. Thirty percent of

the engine's total input energy can be recovered from the jacket water, which can supply hot water at 180 to 200 °F. In addition, the heat from the exhaust air can be used in the desiccants that dry the air entering or leaving the compressor. As seen in Figure 35, gas-driven compressors with heat recovery provide savings even where electricity costs are low. The savings also increase with compressors operating at reduced loads due to the flexibility of gas engines.

Gas engine-driven compressors are currently being offered by Ingersoll-Rand, Dearing Compressor & Pump Co., and LeRoi Dresser. Ingersoll-Rand introduced a 400 hp system in October 1991. The system consists of a Caterpillar 3408 SITA (Spark-ignited Turbo-charged After-cooled) engine, which provides 400 hp at 1800 rpm. The natural gas engine drives a Model 1600 L-NG rotary screw compressor that produces 1600 cfm at 100 psig, at full load and full flow, at ambient design temperature of 100 °F. The initial cost of the compressor is higher than for electric units, but a payback period of 2 years is possible, depending on the cost of electricity. The use of heat recovery can significantly reduce the payback period. Ingersoll-Rand is also developing some smaller units.

Dearing Compressor & Pump Co. offers gas engine-driven compressors ranging from 75 to 600 hp, and has standardized the 75 to 175 hp units. Most of the systems are driven by a Hercules engine. Maintenance costs are estimated at \$0.01 per horsepower-hour. Payback periods range from 1 year to 15 months. Systems with heat-recovery technology have paybacks of 1 year or less ("Engine-Driven Compressors offer Low-Cost Alternative" Winter 1991).

LeRoi Dresser offers gas-driven air compressors in four sizes ranging from 360 to 1500 cfm with pressures from 100 to 150 psi. All system components are from Dresser's standard industrial product line, which simplifies parts replacement. LeRoi is developing a 200 hp unit and evaluating 100, 150, and 300 hp sizes.



(Source: *Natural Gas Applications in Industry*, Winter 1991.)

Figure 35. Annual Savings of a 100 hp Natural-Gas Compressor vs. an Electric Compressor.

7 COMMERCIAL HEATING AND COGENERATION

There are thousands of commercial-sized (0.5 to 10 MBtu/h) boilers and hot water generators at DOD installations. These boilers typically provide space heating, domestic hot water, and process heat for kitchens, laundries, and hospitals. Kitchens, laundries, and hospitals also account for a portion of many installations' peak electric demand. Recent developments in medium-size (50 to 100 kW) packaged cogeneration systems have provided cost-effective electrical power and commercial heating. The commercial-sized heating and cogeneration systems are not typically regulated by air-pollution control agencies; however, California is developing emission standards for all combustion sources, which would provide another incentive for using commercial natural gas technology.

Pulsed-Combustion Steam Boiler

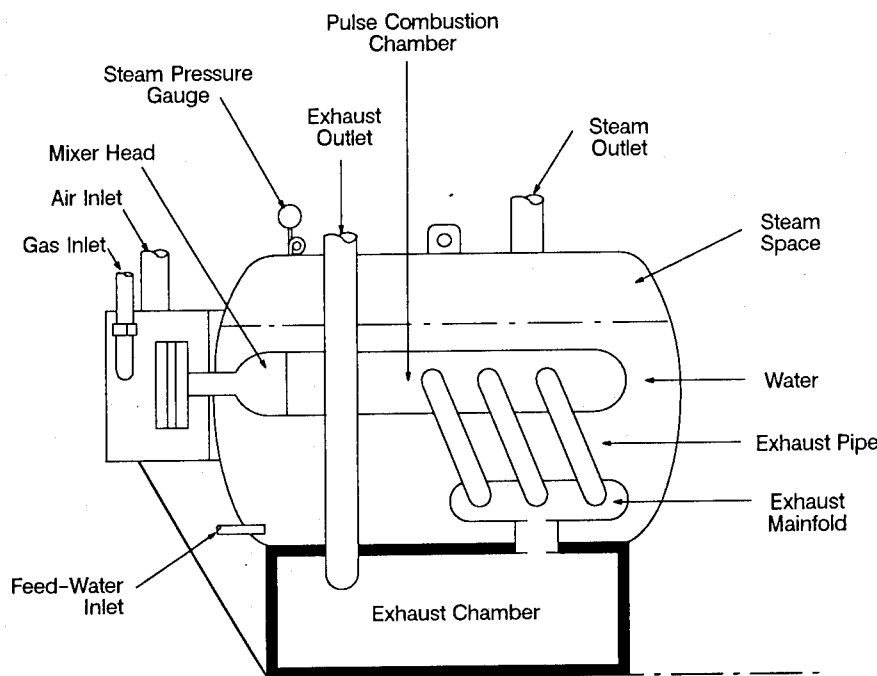
A pulse combustor consists of a combustion chamber, valves, and exhaust pipes designed to regulate the combustion process by the action of combustion-generated waves. Once started, the pulse combustor is self-igniting and vents combustion products without needing a blower or a flue. Pulsed-combustion boilers have many advantages compared to boilers using power or atmospheric burners. The boiler operates with fuel-lean conditions, produces relatively low levels of NO_x emissions, and generates very high heat transfer rates. The high heat transfer of pulse combustion requires less heat exchanger surface while improving efficiency to 85 percent. Pulse combustion also permits modulated operation without a drop in efficiency. Due to its self-venting feature, combustion-air fans or expensive stack systems are not needed. Pulse combustion can be used in low- and high-pressure steam boilers.

With funding from GRI, Forbes Energy Engineering, Inc. has developed a high-input commercial steam boiler using pulsed-combustion technology. A schematic of the unit is shown in Figure 36. The high-input steam boiler was designed to achieve high efficiencies with quiet operation, acceptable emissions, and low manufacturing costs. Prototype units of 0.5 and 2.0 MBtu/h have successfully achieved performance goals of 85 percent efficiency, low noise levels (73 dBA) and half the NO_x emissions of conventional boilers. A 5.0 MBtu/h boiler is being developed with modulated fuel input and dual fuel capability. Modules up to 0.75 MBtu/h are currently available, while a 2.5 MBtu/h unit is expected to be marketed within 2 years, followed by the 5 MBtu/h unit within 5 years.

For air and liquid heating, pulse combustors provide a combination of high efficiency, low manufacturing cost, and low emissions. This technology is also well suited for the conversion of oil-fired boilers. Pulse-combustion concepts have been applied to several applications, including residential furnaces, cooking stoves, and water heating. The Lennox Industries, Inc., Pulse™ Furnace, developed for GRI by the American Gas Association Laboratories, has achieved seasonal efficiencies of over 90 percent. Pulse combustion is also used in an industrial dryer produced by Bepex Corp. Other sections of this report describe these pulsed-combustion applications in more detail.

Microgeneration Technology

The initial costs of medium sized (50 to 100 kW) packaged cogeneration systems have been reduced by high-volume production and factory assembly. Since component, assembly, and maintenance costs do not scale down for smaller systems, the first cost of units less than 50 kW have remained too high for commercial success. Sponsored by GRI and Southern California Gas Company, Tecogen, Inc., is developing advanced control, heat recovery, and packaging technologies for cost-effective microgeneration systems with 81 percent efficiency and high reliability. These concepts will be designed for light commercial applications of various sizes.



(Source: GRI, March 1988.)

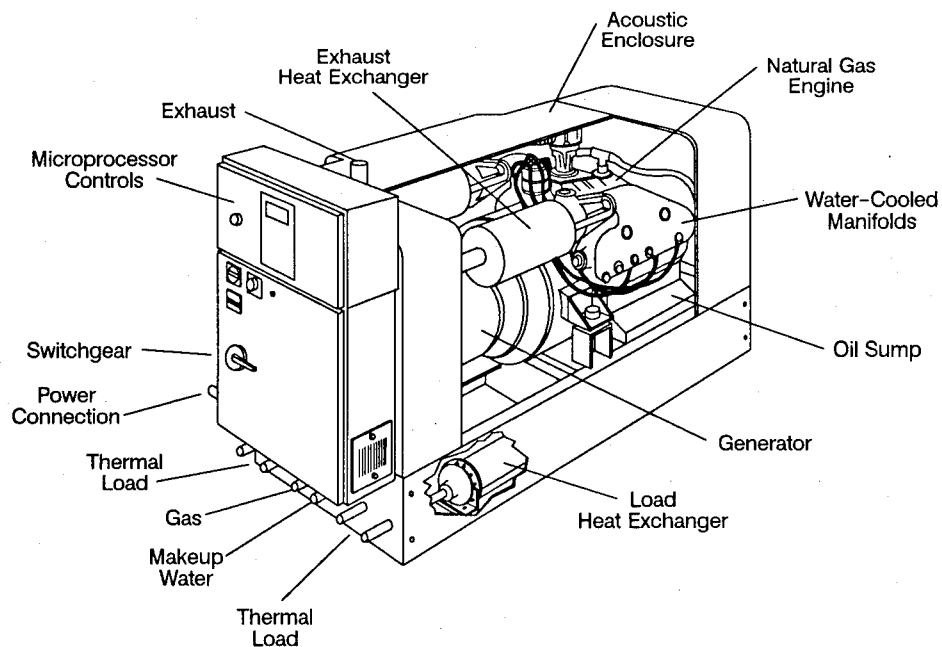
Figure 36. Pulse-Combustion Boiler.

A 30 kW unit was selected for development. The design of the system is shown in Figure 37. As in the Tecogen 60 kW cogeneration system, a modified, high-production-volume engine (Chevrolet 262 cu in. V6) was used. To reduce costs and simplify the system, a load module and controls were built into the system to reduce onsite installation work. The load module contains most of the equipment needed to connect with the building's thermal energy loads, including heat exchangers, pumps, valves, and controls. To simplify piping and eliminate a heat exchanger, the heat-recovery loop is replaced by direct heat recovery from the exhaust manifold and the engine jacket. The controls are designed for remote monitoring and self-diagnosis to reduce maintenance and service costs.

The 30 kW cogeneration module is designed from small and midsize commercial and industrial facilities. The thermal capacity of the system is 219,000 Btu/h of hot water (up to 230 °F). The system has electrical efficiencies of 28.5 percent LHV at 905 Btu/scf and 25.7 percent HHV at 1020 Btu/scf. The overall system efficiency is 89.5 percent LHV, 80.7 percent HHV. One or more module can be installed up to 150 kW.

Tecogen Commercial Cogeneration Systems

Tecogen has developed a 600 kW unit that produces low-pressure steam and variable amounts of electricity. Waste heat from the engine's cooling jacket is compressed to 85 to 125 psig steam. This system offers added flexibility by controlling the use of the compressor to provide the option of low pressure steam or additional electricity as needed. For example, during winter months, the system can provide low pressure steam for space heating and hot water. During the summer, the unit can generate the maximum electricity to offset peak utility charges and the low pressure steam can be utilized for hot water and absorption cooling.



(Source: GRI, March 1988.)

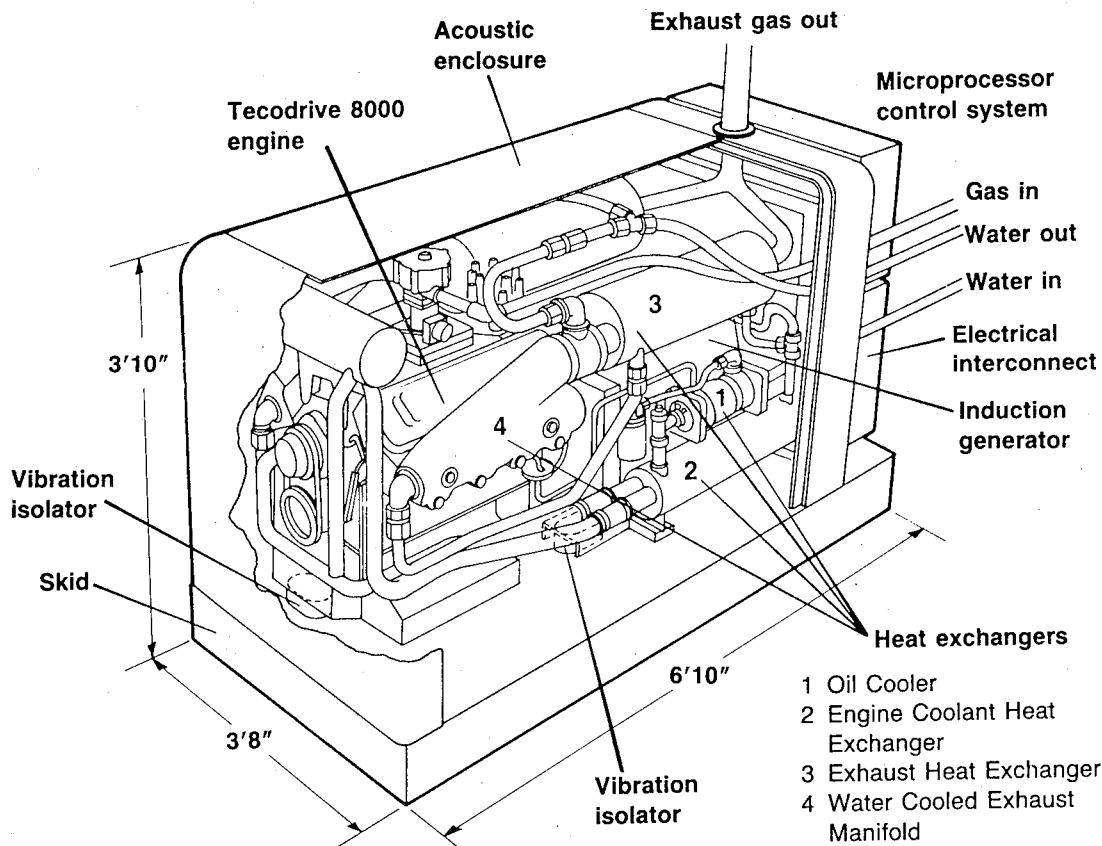
Figure 37. Tecogen 30 kW Cogeneration Module.

The system consists of a natural gas-fueled engine-generator set (Caterpillar G399TC) and a twin helical screw compressor (Atlas Copco ZA4). Programmable controls require minimal attention from operators. With the use of the compressor, the unit can deliver 3100 lb/hr of 100 psig steam and 450 kW of electricity. During low heating demand, 565 kW can be produced with 1100 lb/hr of 100 psig steam and 1750 lb/hr of 15 psig steam. In addition, using waste heat from the engine's cooling jacket and other sources increases the system's overall efficiency to 74 percent, as opposed to 45 percent reported by conventional systems using only exhaust heat (*Identification of Natural Gas Technologies Applicable to U.S. Army Installation* June 1992). Field tests of the Tecogen 600 kW cogeneration system were started in 1989.

Tecogen also offers the CM-60 and the CM-75 cogeneration modules, with capacities of 60 kW and 72 kW, respectively. The CM-60 has a thermal capacity of 440,000 Btu/h of hot water, up to 230 °F, at 18 gallons per minute (gpm). The electrical efficiency is 29.8 percent (LHV, 905 Btu/scf) and 26.4 percent (HHV, 1020 Btu/scf), with an overall efficiency of 93.7 percent (LHV, 905 Btu/scf) and 83.1 percent (HHV, 1020 Btu/scf). For the CM-75, the electrical efficiencies are 31.4 percent (LHV, 905 Btu/scf) and 27.9 percent (HHV, 1020 Btu/scf), with an overall efficiency of 91.6 percent (LHV, 905 Btu/scf) and 81.3 percent (HHV, 1020 Btu/scf). Both systems have the same dimensions and weigh about 3000 lb. The unit is illustrated in Figure 38.

Ultra-Low Emission Gas-Fired Combustor for Space Heaters

Air-heating applications, such as food and malt drying, require very low emissions to prevent contamination. As a result, these industries often use more costly indirect heating methods. IGT and Maxon Corp. are developing an ultra-low-emission gas-fired combustor for low-temperature direct-air space heating. The direct-air heater incorporates a burner concept based on cyclonic combustion technology developed at IGT.



(Source: Tecogen, Inc.)

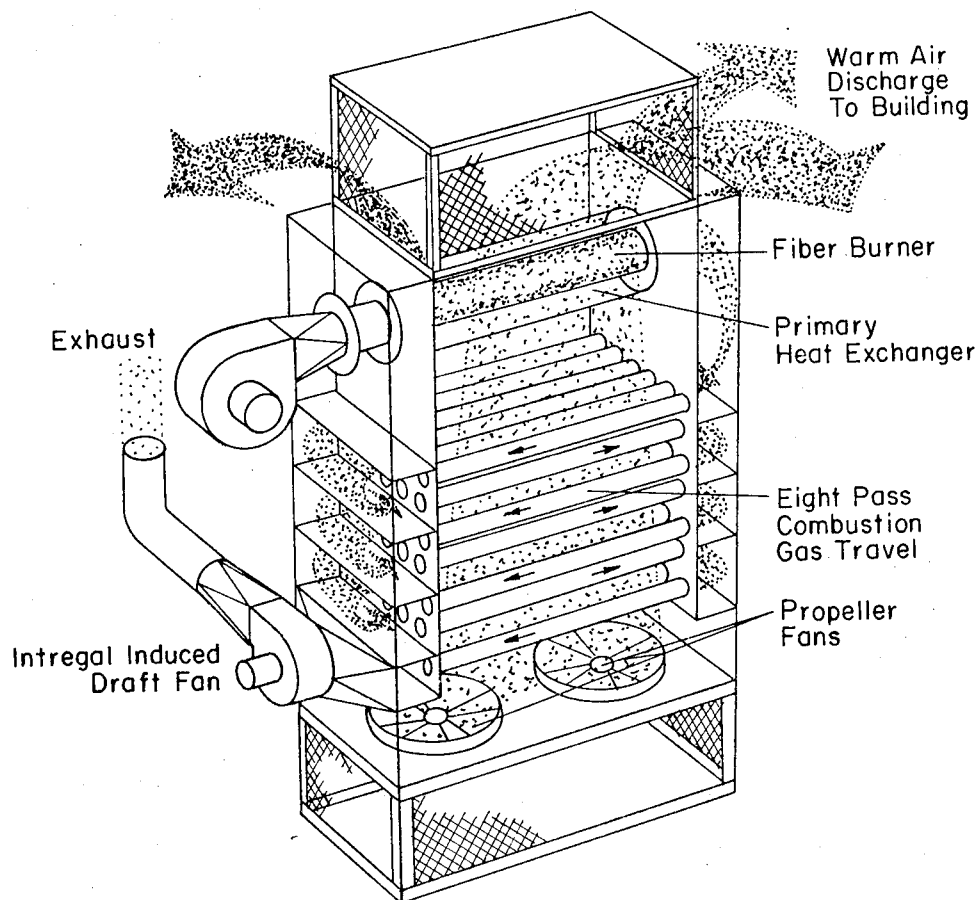
Figure 38. Tecogen 60 kW and 72 kW Cogeneration Systems.

IGT and Maxon have completed proof-of-concept testing, and have developed designs for a cold-flow model and a 1 MBtu/h pilot-scale burner. In experimental tests, the burner successfully demonstrated ultra-low emissions and sufficient turndown ratio. At the designed firing rate and at 15 percent oxygen, NO_x emissions were 0.6 ppm. CO and THC levels were below 3.0 ppm. The test burner remained stable at turndown ratios up to 40:1 and NO_x levels ranged from 0.3 to 1.0 ppm. Currently, a prototype of this technology is being developed to be tested in the field.

Warm-Air Furnace

Space-conditioning makes up a large percentage of total U.S. Army gas consumption. Many recent advances in burner technology and heat exchanger design could be applied to improve the efficiency of space heating technology. With GRI support, Alzeta Corporation and Industrial Air Systems have developed a gas-fired furnace, the Industrial Airsystems 92 Plus™, for heating large open spaces of commercial and industrial buildings such as warehouses, factories, churches, and schools. The furnace design includes the Alzeta Pyrocore™ radiant burner and fully condensing heat exchanger for high-efficiency operation.

The Pyrocore radiant burner consists of a porous ceramic matrix on a 5 in. diameter metallic tube. Premixed air and gas are delivered through the tube and burn flamelessly at the outer surface of the



(Source: GRI, November 1986).

Figure 39. Industrial Airsystems Warm-Air Furnace.

ceramic matrix. As seen in Figure 39, the burner is positioned within a barrel-type heat exchanger. The heat from the burner radiates over its entire area, supplying uniform heat transfer to the primary heat exchanger. Approximately 55 percent of the radiant heat from the burner is transferred to the circulated air stream. The exhaust gas then enters a seven-pass condensing heat exchanger, which consists of stainless steel tubes with 2 in. outside diameters. About 37 percent of the combustion products is recovered in the secondary heat exchanger.

The Industrial Airsystems furnace has an operating efficiency of over 90 percent, and is projected to reduce fuel costs by 20 percent compared to conventional furnaces that are 75 percent efficient. Additionally, the relatively low-temperature (1800 °F) combustion process reduces emission levels far below environmental regulations. The Industrial Airsystems warm-air furnace is offered in various sizes, ranging from 400,000 Btu/h to 6 MBtu/h for commercial and industrial applications.

Commercial Water Heating

Gas Booster Water Heater for Commercial Kitchens

Booster heaters are used in many restaurants and institutional kitchens to raise the temperature of the hot water—usually set at 140 °F—to 180 °F for a final sanitizing rinse. Although electric booster

water heaters are commonly selected for their small size, they produce high operating costs. The American Gas Association Laboratories and Raypak, Inc., have developed an under-the-counter gas-fired booster water heater for GRI at the Gas Appliance Technology Center.

A 130,000 Btu/h ceramic infrared power burner was selected for compactness and low emissions. Gas is premixed with air for combustion. Copper tubing with extruded external fins acts as a heat exchanger delivering 180 °F water at 5.2 gpm. Solid-state temperature controls and a ceramic hot surface ignitor produce a heatup within 3 to 5 seconds. An internal water loop is connected to a built-in 4-gal storage tank to support quick heatup by continuous circulation. The unit can vent directly into the steam hood of a dishwasher or to the outside through a wall or ceiling.

The capacity of the gas-fired heater is equivalent to a 30 kW electric booster heater. Its thermal efficiency is 80 percent. The gas-fired booster heater is compact (32 in. high) for under-the-counter installation and direct replacement of an electric heater. The NO_x emission levels are below 40 ppm, with CO emissions less than 50 ppm. The payback period for the gas-fired booster is expected to be less than 9 months because of lower energy costs. Field tests are currently being conducted, and the heater was expected to become commercially available in 1992.

8 COMMERCIAL COOLING

As DOD installations have improved the working conditions and comfort of their facilities, the air conditioned building space has increased, resulting in higher electric consumption and cost. Alternatives to electric-driven cooling systems described in this section include natural gas absorption chillers, engine-driven chillers, desiccant cooling, and heat pumps. These emerging technologies can supply from 5 tons (heat pumps) to 500 tons (engine-driven chillers) chilling capacity.

Triple Effect Absorption Chiller

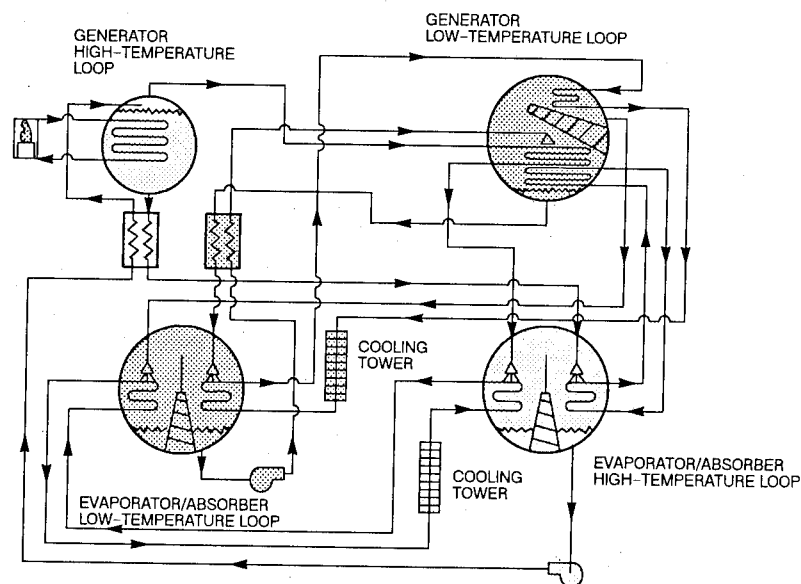
Absorption cooling systems are heat-operated refrigeration systems that use pumps, heat exchangers, and pressure vessels in the place of the compressor used in conventional mechanical refrigeration. In mechanical refrigeration systems, a fluid vapor is compressed and the latent heat is removed by a condenser. The fluid then travels to an evaporator at lower pressure. As the liquid expands, it absorbs the surrounding heat. The vapor is then recycled to the compressor, and the process begins again.

Absorption chillers recover low-grade industrial waste heat from cogeneration or process steam and produce chilled water. Absorption cooling provides air-conditioning without the use of chlorofluorocarbons (CFCs). In addition, the relatively low number of moving parts makes absorption coolers very reliable. Absorption systems are cost effective when their high capital costs are offset by the difference in the cost of heat required to drive them compared to the cost of power needed to drive a mechanical system. Absorption chillers can provide an efficient and environmentally safe alternative for space cooling, especially in cogeneration applications with a heat source already in place.

Gas industry researchers and the Trane Co. are developing a triple-effect absorption chiller with a projected capacity of 100 tons and greater for large commercial and institutional applications. The concept is based on a high-temperature topping cycle followed by a low-temperature bottoming cycle. As shown in Figure 40, the triple-effect chiller consists of a conventional single-effect chiller combined with a smaller, higher-temperature chiller. The high-temperature topping cycle is fueled by natural gas combustion, producing a 450 °F generator temperature. Heat rejected from the topping cycle at about 200 °F is used as the energy source for the conventional lithium-bromide bottoming cycle. The bottoming cycle rejects heat at 100 °F to a cooling tower. Both cycles supply 44 °F water to the building's distribution system with the topping cycle providing 40 percent of the overall cooling.

The triple-effect technology is expected to achieve a coefficient of performance (COP) of 1.5, and an increase in efficiency of 50 percent over state-of-the-art double-effect absorption chillers. The advantage of the triple-effect chiller is that it offers significantly lower operating costs while maintaining the same manufacturing costs as a double-effect system. Current development involves identifying corrosion-resistant materials and an environmentally acceptable absorption fluid and refrigerant. Trane recently constructed a 190-ton prototype, which is currently being evaluated. Field tests are planned for 1993 or 1994.

Trane is also developing a microprocessor control system to simplify the operation of conventional absorption chillers. The control system is expected to be commercially available in 1993.



(Source: GRI, December 1990.)

Figure 40. Diagram of the Triple-Effect Cycle Used in Trane's Absorption Chiller.

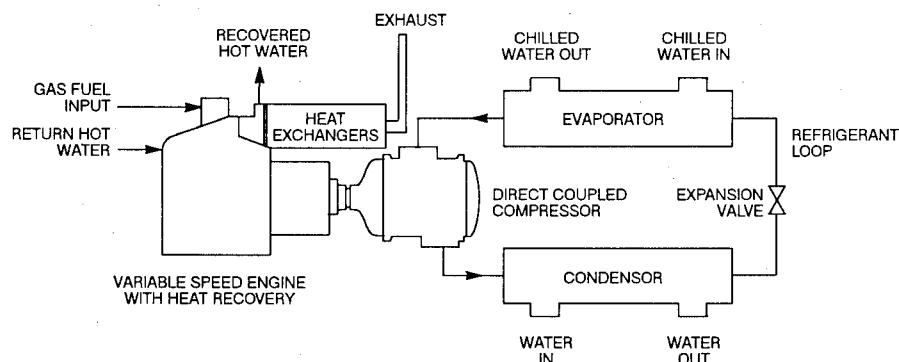
Gas Engine-Driven Cooling Systems

Most gas-fired engine-driven cooling systems are essentially conventional mechanical cooling systems in which the electric motor is replaced by a gas-fueled engine. Such systems also require modifications in compressor operation and drive mechanisms. While electric motors have high durability and low maintenance requirements, advances in design and materials are making gas-powered engines a competitive alternative. Unlike constant-speed electric motors, the speed of gas engines can be adjusted to the cooling load, to improve energy efficiency. In addition, the heat produced by a gas engine can be used for hot water or space heating. Gas driven-engines also eliminate peak electric summer loads associated with conventional electric units, further reducing energy costs.

Gas Engine-Driven Chillers

With support from GRI, Tecogen has developed a high-efficiency 150-ton gas engine-driven chiller. The chiller is based on the automotive engine, which is durable but less expensive than an industrial engine due to high-volume production. Carrier Corp. is jointly marketing it with Tecogen. The company expects the engine-driven chiller to reduce customer cost by 30 percent or more.

The Tecogen 150-ton chiller is based on a modified 454-cu in. General Motors marine engine. A schematic of the system is shown in Figure 41. The natural gas-fueled engine drives a screw compressor to produce about 150 tons of cooling. The variable speed engine provides excellent performance at partial load, and can operate above rated capacity without excessive engine wear. Waste heat from the engine coolant jacket is recovered as hot water, which can be used for domestic water heating, process needs, or to drive a supplemental single-effect absorption chiller to provide an additional 30 tons of cooling capacity.



(Source: GRI, June 1988.)

Figure 41. Tecogen 150-Ton Chiller.

The 150-ton chiller has very low operating costs compared to electric units, and offers an estimated payback period of less than 3 years based on energy prices in most major U.S. cities. The chiller also has low routine maintenance costs, with a maintenance interval of 2000 hours. The unit can replace electric chillers with minor site modifications.

The 55-ton and 80-ton Trane chillers are driven by a Hercules industrial engine powered by natural gas, but they can also accommodate other types of fuels. Heat from the engine water jacket can be recovered for heating water, reheat, or regeneration of desiccants for additional energy savings. The chiller operation is electronically controlled. Trane is also currently developing a 110-ton unit.

Engine-Driven Air-Conditioning Unit

Conventional air-conditioning units driven by gas engines offer high efficiency and reduce peak electric demand. Thermo King Corp. has developed the GTC-1, a 15-ton rooftop air-conditioner for smaller commercial buildings. The air-conditioning unit consists of a Hercules gas-fueled engine that drives a Thermo King compressor. A gas engine-driven unit can efficiently meet fluctuations in cooling demand by varying its speed. This provides a range of outputs. The cooling unit has four modes of operation: 2400, 1500, and 900 rpm with the compressor at full load, or 900 rpm with the compressor at 50 percent load. It is most efficient at 900 and 1500 rpm. All ancillary components except the air-circulation fan are driven by the gas engine.

The cooling capacity is 15 tons and the unit has a COP of 0.99. An optional 80-percent-efficient furnace can also be added to the rooftop system to provide heating at a capacity of 240,000 Btu/h. The service interval is 2000 to 3000 hours for an oil change, spark plugs, and engine filters. The dimensions

of the unit are 12 ft, 11 in. long, 6 ft, 4 in. wide, and 4 ft, 2 in. high. The 15-ton rooftop unit has been commercially available since 1990 and a 25-ton unit is expected to be available soon.

More recently, Thermo King has introduced a 15-ton split system, in which the refrigeration system is located outdoors with an indoor blower and evaporator coil. This system was designed to accommodate a wider range of buildings with zoned heating and cooling systems.

Tecogen also is field-testing a 25-ton packaged rooftop air-conditioning unit that consists of a Carrier Weathermaker II converted to a gas-engine-driven system. The system has high-efficiency controls that include variable engine speed, and two stages of unloading on the reciprocating compressor with a projected COP of 0.99. Market entry is planned for late 1992.

Desiccant Cooling

Separate controls for humidity and cooling can provide increased comfort and efficiency. Desiccant systems can provide low-cost, high-efficiency cooling without the use of CFCs. Recent advances in desiccant material have produced an increase in COP from 0.6 to over 1.0 for desiccant cooling systems, with an even higher COP for heating. Due to minimal electrical requirements, desiccant systems also eliminate the peak electric demand associated with conventional air-conditioners.

Desiccants are liquid or solid materials that soak up humidity and release water vapor when heated. For space-conditioning applications, the desiccant is deposited on a "honeycomb" wheel between two air streams. The moisture from the indoor air is absorbed on one side and then released on the other side into the exhaust air. Sensible cooling is provided by incorporating evaporative coolers in the pass of the dry air or an externally refrigerated cold liquid. Desiccant integrated cooling and heating is currently being used in commercial applications. With further development of desiccant materials and lower production costs, desiccant systems have the potential to provide efficient, low-cost, and environmentally sound cooling.

Cargocaire Engineering Corp., with support from GRI, has developed an integrated gas and electric cooling system for supermarkets that combine 20 tons of gas-regenerated desiccant cooling with 30 to 60 tons of electric cooling. In addition to cooling, The SuperAire™ system also reduces frost buildup, which lowers refrigeration operating costs. The unit economically provides the equivalent of 40 to 80 tons of electrical cooling. A diagram of the SuperAire™ system is shown in Figure 42. The system is based on a lithium chloride HoneyCombe™ dehumidification system. The dehumidification system consists of a rotating wheel containing desiccant, which removes moisture from the unconditioned supply-air stream. A second air stream heated by Thermo Electron Corp. heat-pipe technology, regenerates the dehumidifier, increasing the burner's efficiency to 85 percent. The air stream containing the moisture is then released outside the building. An indirect evaporative cooler is used to remove additional heat from dried air leaving the desiccant wheel. The electric air-conditioner is also cooled by the water circulation system, which reduces compressor power costs by 40 percent. A simple payback period of incremental system costs is estimated at less than 2 years.

Cargocaire is also developing a gas-fired desiccant dehumidification system for hotel air-conditioning based on the same concepts as the SuperAire™. The system is expected to lower operating costs because the electric air-conditioners can be downsized and should also reduce moisture-related damage. Commercialization of this system is projected for 1992.

Tecogen is developing a gas-fired solid desiccant-based cooling system for small commercial and residential applications. After the air is dehumidified, it is sensibly cooled by heat exchange and

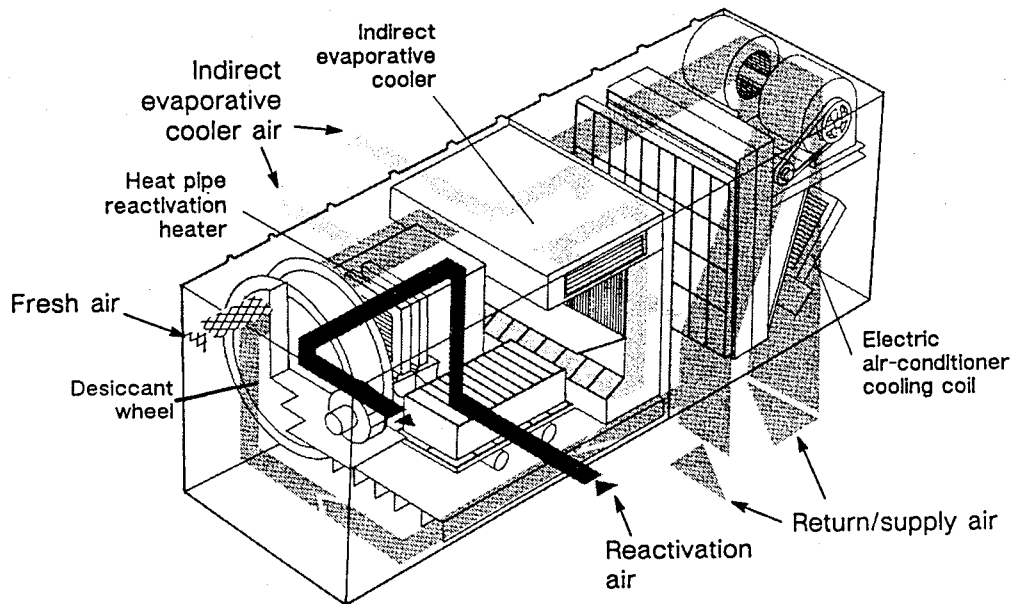


Figure 42. Diagram of the SuperAire™ Cooling System.

evaporative cooling. Laboratory tests have demonstrated cooling capacities of 8 tons and COPs of 1.5 at ARI (American Reference Institute) rating conditions ("Triple-Effect Absorption Chiller" December 1990). A 1000-cfm unit was tested at 5 tons with a COP of 1.7. With improved component design, especially heat exchangers, cooling capacities of 10 tons and COPs of 1.9 are projected.

Gas-Fired Heat Pumps

Gas heat pumps (GHPs) can provide both heating and cooling for space-conditioning applications. GHPs can produce efficient residential heating using just one-fourth of the energy used by a high-efficiency furnace. The GHP also provides cost-effective cooling, which reduces peak electric demand associated with conventional air-conditioning.

GRI and Aisin Seiki Co., Ltd., have developed a 5-ton engine-driven gas heat pump to provide heating and cooling for the light commercial market. The heat pump is based on a conventional vapor-compression refrigeration cycle. The unit consists of two scroll compressors driven by a three-cylinder, low-noise, reciprocating gas engine. Both the engine and the compressor are derived from automotive components to provide durability and low cost. Engine speed can be changed to match variations in heating and cooling loads. Recovery of waste heat from the engine also improves the efficiency of the system. An auxiliary gas-fired hydronic heater is included to provide supplemental heating, if necessary. A microprocessor control system optimizes system performance.

The seasonal cooling efficiency of the system is 100 to 120 percent, with a seasonal heating efficiency of 120 to 150 percent. In addition to the low operating costs of the system, the combination of heating and cooling from a single unit also reduces capital costs. The Aisin heat pump is currently being field tested and the unit is projected to be commercially available by 1993.

9 COMMERCIAL KITCHEN APPLICATIONS

As discussed in the chapter Commercial Heating and Cogeneration, kitchen equipment accounts for a portion of many installations' peak electric demand, particularly troop training and deployment installations. Several technologies are under development specifically for commercial kitchens—including ovens, broilers, griddles, ranges, and hot-water heaters.

Commercial Combination Steam/Convection Oven

Combination steam and convection ovens are used for a variety of institutional cooking applications, including baking, roasting, moist roasting, and steaming. Electric combination ovens use resistance heaters that offer limited input capabilities and a tendency for early failure caused by scale deposits and overheating. A full-size combination gas oven has been developed by Tecogen, Inc., and GRI.

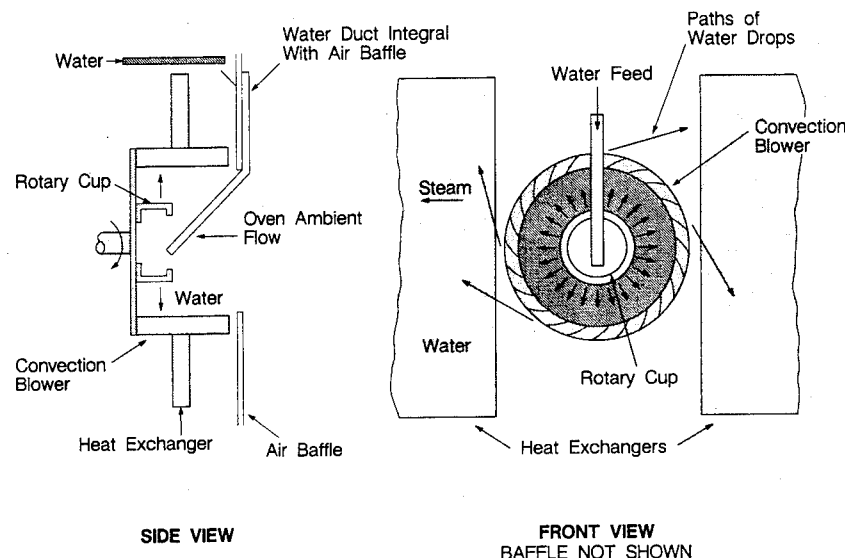
As shown in Figure 43, the combination gas oven uses a rotary cup atomizer with a flat-plate heat exchanger in the place of a steam boiler for lower cost, less space and easier cleaning. The atomizer, which disperses water against the heat exchanger, produces steam instantly with lower waste consumption and operational simplicity. A two-pass combustion gas system has the inlet and exhaust ducts on the same end of the heat exchanger to avoid thermal stresses and maximized oven temperature uniformity. Fins are attached to the combustion side of the heat exchanger to improve heat transfer and provide structural integrity. Solid state controls regulate temperature, time, and humidity.

The gas combination oven costs less to buy than electric ovens and costs less to operate due to improved productivity and higher fuel efficiency. Oven tests demonstrate a reduced cooking time by 15 to 40 percent (*Combination Broiler/Griddle* July 1990). The prototype combination oven was developed by modifying a Jade Range, Inc., convection oven. Jade Range is marketing three models of gas-fired steam/convection ovens, including an oven with rangetop burners and standalone ovens of medium- and full-size capacity.

Combination Broiler/Griddle

To improve cooking efficiency and decrease cooking time, a griddle was designed with an electric broiler to broil food from above while frying it on the griddle. The disadvantages of the electric broiler are its fragility, the high replacement cost of the quartz heating elements, and the difficulty cleaning the unit. With support from GRI, Lang Manufacturing Co. and the AGA developed a gas-fired infrared broiler section for installation on top of gas-fired griddles.

Output of the gas-fired infrared broiler section is 35,000 Btu/h and it measures 18 in. square. Since the overhead broiler uses both convective and radiant heat transfer while the griddle uses only conductive heat transfer, the broiler would cook faster than the griddle. Consequently, the radiating tile output and heat flux of the broiler were designed to match the cooking rate of the griddle. Fan-assisted combustion was used to increase the heatup speed and operator comfort. In tests, the gas-fired infrared broiler/griddle decreased cooking time for a hamburger to 3.5 minutes compared to 4 minutes with the electric broiler and 10 minutes on a conventional griddle. The gas griddle also produced better browning characteristics and increased operator comfort. The gas-fired combination broiler/griddle was introduced to the market by Lang Manufacturing in 1990.



(Source: GRI, March 1988.)

Figure 43. Diagram of Rotary Cup Atomizer Used in Tecogen Steam/Convection Oven.

Gas-Fired Rethermalizing Oven

In a large-volume food preparation, food typically is cooked in a conventional oven, chilled quickly to avoid bacteria growth, then "rethermalized" (reheated) several days later for serving. This process saves labor costs since skilled cooks can prepare food in advance. Conventional rethermalizing ovens are usually electric, which involves high energy costs and the expense of replacing the electric resistance heaters. With GRI, AGA, and PMI Food Equipment Group/Vulcan-Hart developed a gas-fired oven that can be used for rethermalization as well as conventional convection cooking.

The rethermalization oven is direct-fired with an induced draft burner and specially developed electronic controls. The heat input is 90,000 Btu/h. The gas oven can accommodate ten steam-table pans (12 in. x 20 in. x 2 in.) and its modular design can be expanded into a 22 pan oven. The operating costs of the gas oven are expected to be 40 percent less than for an electric unit. The gas rethermalizing oven also provides a lower purchase price, easier maintenance, and greater flexibility than electric units.

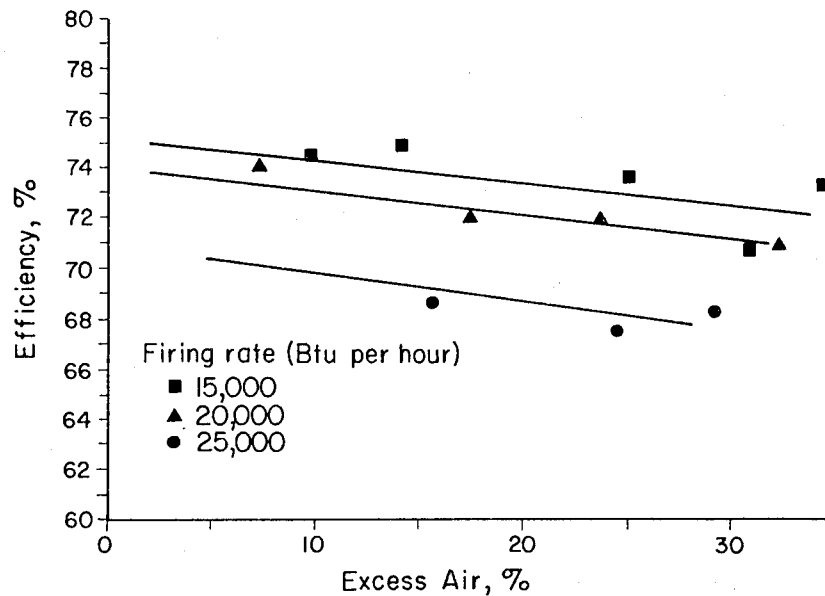
High-Performance Commercial Burner

Battelle-Columbus Laboratories and Garland Commercial Industries, Inc., with GRI, have developed a new powered burner for commercial open-top ranges. The powered burner provides the same usable output as conventional burners, but at a reduced input. This results in lower operating costs and better performance.

The preliminary work for this project was performed by AGA Laboratories in 1983. That study found that the efficiency of a conventional atmospheric burner is reduced because of excess air rising from

the burner box through the secondary air openings around each burner. A decrease in excess air coupled with a lower firing rate produces an increase in burner efficiency, as shown in Figure 44. The powered burner uses a fan to premix the combustion air with gas. The air-gas mixture is then ignited and forced through a specially designed, low-cost burner cap with slotted discs. The cap effectively distributes the flame uniformly across the bottom of a pot or pan. The modular design of the cap allows various sizes of burner (15,000 to 30,000 Btu/h) to be constructed by changing the number of slotted discs in the cap.

The powered burner has an efficiency 60 percent or greater, compared to conventional oven-top range burners with 45 percent efficiency. This efficiency improvement can result in a payback period of less than 3 years. The burner also reduces CO emissions and the amount of heat lost to the environment. The powered burner is manufactured and marketed by Garland Commercial Industries, Inc., which also offers a single setpoint (full on/off) powered burner.



(Source: GRI, December 1986.)

Figure 44. Effect of Firing Rate and Excess Air on Burner Efficiency.

10 RESIDENTIAL APPLICATIONS

Troop training and deployment installations provide housing for both enlisted personnel and their dependents. Residential energy costs can be substantial because the buildings are occupied 24 hours a day, as opposed to administrative buildings. One recent advance in natural gas technology is the residential engine-driven heat pump. It is dependent on energy price differentials and is most cost effective in moderate to warm climates.

Residential Cooling

Residential Engine-Driven Gas Heat Pump

The Battelle-Columbus Division and GRI have developed a 3-ton engine-driven gas heat pump for residential applications. The gas heat pump provides a gas-fueled alternative to the conventional gas furnace/electrical air-conditioning systems used by most homes. The gas heat pump offers lower overall energy costs than conventional systems, with improved efficiency and comfort. The heat pump system uses a conventional vapor-compression refrigeration cycle for cooling capacity of 3 tons, and a parallel water-glycol engine-heat-recovery system to supply a heating capacity of 53,500 Btu/h. The unit consists of a 5-hp single-cylinder natural gas engine selected for reliability, performance, and emission requirements. Based on endurance tests, the engine design life is expected to exceed 40,000 hours. The engine drives a high-efficiency reciprocating compressor. A microprocessor-based controller regulates fan speed, engine speed, and cycling rates to optimize efficiency, comfort, and reliability. The control system also supplies diagnostic information to simplify servicing and troubleshooting. An optional gas-fired hydronic (hot water) heating unit can be used for supplemental heating.

The gas heat pump offers improved performance with a seasonal heating efficiency of 123 percent (or a COP of 0.9). The operating costs of the heat pump are the lowest of any existing residential space-conditioning system ("Residential Engine-Driven Gas Heat Pump" November 1990). Heat recovery from the engine can provide additional heating capacity in the winter, or hot water for use all year. In addition to lower operating costs by using gas for cooling, the electric auxiliary components in the heat pump system were designed for minimal power consumption. The maintenance interval of the unit is 1 year.

Following the completion of initial field tests, the technology was transferred to York International. A 100-unit field demonstration is currently being conducted, and commercialization of the residential heat pump is projected for 1993.

11 SUMMARY

Although electricity consumption accounts for about 33 percent of DOD energy use, it comprises 66 percent of total costs. Natural Gas appears to be a promising alternative to the use of electricity and other fossil fuels. This report highlights dozens of potential DOD applications in which state-of-the-art gas-fueled devices could economically reduce or end reliance on technology powered by coal, oil, or electricity.

Natural gas offers a competitively priced, dependable, environmentally-sound energy alternative for DOD installations. Analysis shows that natural gas offers environmental benefits over other fossil fuels; for example, natural gas cofiring and regeneration have been shown to reduce hazardous emissions. Industry figures show that gas prices should remain stable in the foreseeable future, competitive with other energy sources.

Innovative, cost-saving technologies are available for installation applications ranging from residential cooling and heating, to industrial process applications, power generation and cogeneration, to food processing. The survey of new and emerging natural gas technologies here indicates that such products will be readily available commercially throughout the decade and beyond.

With continuing research, development, and field tests in new application areas, innovative natural gas systems should be readily available to installations through regular commercial channels.

METRIC CONVERSION FACTORS

1 in.	=	25.4 mm
1 ft	=	0.305 m
1 yd	=	0.9144 m
1 cu in.	=	16.39 cm ³
1 cf	=	0.028 m ³
1 sq ft	=	0.093 m ²
1 sq in.	=	6.452 cm ²
1 ton	=	907.1848 kg
1 lb	=	0.453 kg
1 lb/hr	=	0.126 g/s
1 psi	=	68.9476 kPa
1 psi	=	6.89 kPa
1 torr	=	133.322 Pa
1 rpm	=	6.0 degrees/sec
1 gal	=	3.78 L
1 gpm	=	0.06308 L/sec
°F	=	(°C + 17.78) × 1.8
1 torr	=	133.322 Pa
1 kWh	=	3,413 Btu
1 Btu/lb	=	0.556 cal/g
1 hp	=	33,479 Btu/hr
1 hp	=	9.803 kW

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ABBREVIATIONS AND ACRONYMS

ABB	Asea Brown Boverie
ADDS	Army DEIS Data System
ADL	Arthur D. Little (Inc.)
AGA	American Gas Association
AGM	Advanced Glass Melter
ALCOA	Aluminum Company of America
ARI	American Reference Institute
Btu	British thermal unit
CAF	cement advanced furnace
CDG	Compu-Dry Gas
CERI	Canadian Energy Research Institute
CFC	chlorofluorocarbon
cfm	cubic feet per minute
CIS	Commonwealth of Independent States
CONUS	Continental United States
COP	coefficient of performance
dBa	decibel(s) adjusted
DEIS	Defense Energy Information System
DOD	Department of Defense
DOE	U.S. Department of Energy
EAF	electric arc furnace
EERC	Energy and Environmental Research Corp.
EPRI	Electric Power Research Institute
ERC	Energy Research Corp.
ESP	electrostatic precipitator
FY	Fiscal Year
GE	General Electric
GHP	gas heat pump
gpm	gallons per minute
GRI	Gas Research Institute
GRID	Gas Research Institute Digest
GRSI	gas reburning/sorbent injection

ABBREVIATIONS AND ACRONYMS (Cont'd)

HHV	higher heating value
hp	horsepower
HRSG	heat-recovery steam generator
IECEC	Intersociety Energy Conservation Engineering Conference
IFC	International Fuel Cells (Corp.)
IGT	Institute of Gas Technology
KTI	Kinetics Technology International (Corp.)
kW	kilowatt
kWh	kilowatthour
KTI	Kinetic Technology International Corporation
LHV	lower heating value
LNG	liquified natural gas
LPG	liquified petroleum gas
mcf	thousand cubic feet
MCFC	molten carbonate fuel cell
MCP	M-C Power (company)
MIT	Massachusetts Institute of Technology
MSW	municipal solid waste
MW	megawatt
NES	National Energy Strategy
NES	Northeastern Station
NOx	nitrogen oxides
ONSI	On-Site (Inc.)
OSHA	U.S. Occupational Safety and Health Administration
PAFC	phosphoric acid fuel cell
ppm	parts per million
PPMF	Pre-Pilot Manufacturing Facility
psi	pounds per square inch
psig	pounds per square inch gage
R&D	research and development
ROI	return on investment
rpm	revolutions per minute

ABBREVIATIONS AND ACRONYMS (Cont'd)

SITA	Spark-ignited Turbo-charged After-cooled
scf	standard cubic feet
SCR	selective catalytic reduction
SER	single-end recuperative
SIGECO	Southern Indiana Gas & Electric Co.
SOFC	solid oxide fuel cell
SOx	sulfur oxides
STIG	steam-injected gas (turbine)
tcf	trillion cubic feet
TERA	Total Energy Resource Analysis
THC	total hydrocarbons
tpd	tons per day
TSP	total suspended particulates
USACERL	U.S. Army Construction Engineering Research Laboratories
USEPA	U.S. Environmental Protection Agency

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